Spin of the M87 Black Hole

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Spin measurement of the 6.5 billion solar mass black hole in M87 from the Event Horizon Telescope image is the latest in a series that span a wide range in values, but that tend to share the feature of corotation between the accretion flow and black hole. The spin paradigm for black holes predicts very high black hole spin which in that framework is produced in its last significant merger. High black hole spin appears to be ruled out in the gap paradigm, however, which predicts early formation with a mass already in excess of 4 billion solar masses. In this picture, the black hole experiences slow evolution as it departs from its original radio quasar phase and over billions of years not only fails to double its mass but also falls short of regaining its original high spin, such that it is now compatible with a corotating accreting black hole whose dimensionless spin fits best in the range $0.2 < a < 0.5$.

1. Introduction

M87 is a low redshift ($z \approx 0.004$) radio galaxy in the Virgo cluster about 54 million light years away whose central supermassive black hole is estimated at 6.5 billion solar masses by the Event Horizon Telescope,[1] a result that follows two decades of measurements.[2–4] Its dimensionless black hole spin has been estimated at $a \approx 0.98,[5] a \approx 0.9,[6] a > 0.8,[7] a > 0.65,[8] a > 0.2,[9] a \approx 0.1,[10] 0.1 < a < 0.5.[11]$ Despite a variety of model-dependent assumptions and values of spin, corotation between the black hole and disk is preferred. We discuss model constraints stemming from the large black hole mass and the low redshift value of M87.

The spin paradigm for black hole accretion and jet formation emerges from the seminal analytic exploration of jet power from black hole spin-energy extraction.[12–16] Although the paradigm emerged in the thin accretion disk context, it has evolved into a framework that requires thick disks, at least in the inner parts, in order to model the powerful, collimated jets, that are observed in radio galaxies and quasars. The gap paradigm,[17] on the other hand, opens a window for the most effective jet formation via retrograde accretion or counterrotation between the disk and black hole. Because the most powerful radio quasars in this model emerge from thin disks, thick disks are not required for jet formation. While both models predict corotation for the M87 black hole, we show that they predict nonoverlapping regions of the prograde spin space.

In Section 1, we introduce the spin paradigm and the gap paradigm and their different predictions for the spin of the Fanaroff-Riley I (FRI) radio galaxy M87. In Section 2, we conclude.

2. Discussion

2.1. The Spin Paradigm

The spin paradigm for black hole accretion and jet formation amounts to a collection of ideas dating to the 1970s when accretion power and black hole spin-energy extraction were placed into a proper theoretical context.[12,18] This led to a picture for powerful jets based on the value of the dimensionless black hole spin.[16] In the following decades and with support from numerical simulations, the high/low black hole spin dichotomy for jetted/nonjetted black holes was enhanced by the introduction of advection dominated accretion flows[19] associating jets with thick inner disk regions, necessary for collimation and acceleration. Simulations, however, struggled to produce jet efficiencies that can explain observations.[20,21] This need to find a more efficient jet efficiency led to the introduction of steeper spin dependence at high spin[15] and floored magnetospheres.[22] Even in the latter context where black holes are drowned in magnetic fields by construction, jet efficiency is high enough to match observations only at high spin. The reasons for this may have something to do with the magnetic tower effect.[23,24] Retrograde accretion, on the other hand, appears more amenable to the magnetic tower effect.[24]

While radio quiet active galactic nuclei (AGN) are prescribed to inhabit a black hole spin range $0 < a < 0.15$, radio loud AGN instead produce jets whose power is proportional to black hole rotation to the sixth power for thick disks, a much steeper dependence than in the original Blandford–Znajek effect.[25] For the black hole in M87 which has a powerful FRI radio jet extending thousands of parsecs from the center of M87 observed at 14° from our line of sight, these ideas require its black hole to be spinning in corotation with its disk at more than 90% of its maximum possible value. General relativistic simulations have also explored disk orientation, showing that the prograde accretion regime produces more efficient jets than the retrograde one.[25] From the perspective of general relativistic simulations, an even higher retrograde spin than prograde spin could match jet power, so the retrograde regime is not entirely ruled out for M87. Simulations have also recently made strides toward implementing radiative losses (e.g.,[26]) but the impact of this is too

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The gap paradigm for black hole accretion and jet formation 2.2. The Gap Paradigm

The gap paradigm for black hole accretion and jet formation amounts to a collection of ideas that were combined in 2010 including flux trapping, retrograde accretion, and eventually grounded in the size of the gap region between the accretion disk and the black hole horizon. Applying basic phenomenology to the Blandford–Znajek and Blandford–Payne mechanisms, the gap paradigm prescribes Fanaroff–Riley II (FRII) jet morphology that is formed in retrograde configurations as a result of the large gap region between the inner disk and the black hole horizon and FRI jet morphology for corotating configurations and mostly advection-dominated accretion. Because retrograde accretion tends to be unstable, a restrictive parameter space that connects the angular momenta of the black hole and accretion disk and indirectly the masses, has been obtained. These conditions make it so that retrograde accreting black holes constitute a minority among all accreting black holes. The reason why the state of accretion does not affect the presence of the jet in retrograde configurations is due to the absence of disk suppression in retrograde states. Instead, the suppression of the jet by the disk occurs in radiatively efficient disks whose inner edge is close to the black hole, hence in the higher prograde spin regime. A fundamental feature of the gap paradigm that is inevitably incorpo- rated into the model is the time evolution which is dictated by the accretion process. Because retrograde configurations spin black holes down, there is a sequence of states that emerge in the paradigm, namely prograde accretion states in the future of retrograde accretion states. This does not mean that prograde accretion states cannot make up initial configurations, simply that if they do constitute initial states, they will also constitute future states. In other words, the cause-and-effect relation is in the sequence retrograde $\rightarrow$ prograde and not the other way around.

Although the retrograde to prograde evolution is an inevitable consequence of accretion, jet feedback can affect the future accretion state and therefore contribute to determining whether the disk remains thin or evolves into an advection dominated flow. These differences have been applied to explain a host of recent observations. For our purposes, we focus on the evolution of objects that can model M87, which amounts to an originally retrograde accreting black hole surrounded by a radiatively efficient thin disk that was formed after a merger and that evolved via accretion (Figure 1). This powerful FRII quasar (Figure 1, lowest panel) produced a jet feedback that dramatically affected the entropy of the interstellar medium and eventually altered the mode of accretion on relatively short timescales compared to systems whose jet feedback is weaker. As a result, the accretion disk evolved into a hot, advection-dominated state, within only a few million years (Figure 1, second to lowest panel). Of crucial importance here is the state transition of the disk, which as an advection-dominated accretion flow (ADAF) accretes at or below 0.01 times the Eddington accretion limit, the theoretical boundary between advection-dominated and radiatively efficient disks.

Continued accretion spins the black hole down to zero spin and eventually into corotation with the disk. When the spin is prograde but still too low for a powerful jet to form (Figure 1, second panel from top), we have an FR0 radio galaxy and continued accretion turns such objects into FRI radio galaxies like M87 as a result of the increase in spin. As mentioned, the crucial thing to note is that 100 million years is the time required to spin the black hole up to high corotating values. However, the disk rapidly transitioned to an ADAF (the FRII low-excitation radio galaxy (LERG) state in Figure 1) which means continued accretion will require 100 times as long which brings the timescale to 10 billion years. Because we assumed an accretion rate that is at the boundary between ADAF and thin disk, this amounts to a lower limit on the timescale. A more reasonable estimate for that time $T$ would be 10 billion years $< T < 100$ billion years. Dry mergers if anything would increase the timescale as they would offer the possibility of resetting the clock if the inner accretion ends up retrograde. The hot gas in which the system is embedded would continue to produce an ADAF onto the black hole which would be the equivalent of a system similar to the second panel from bottom in Figure 1. As a result, the idea that the black hole spins rapidly in corotation with the disk appears unlikely in this model. However, M87 displays a powerful FRI jet which means its spin is not only prograde but also above about 0.2. Note also from Figure 2 that the amount of mass that needs to be accreted in the prograde regime to increase the spin by 10% increases as the spin increases. If the mass increased by 1.5 its original value, Figure 2 shows that its spin becomes about 0.5. This means its original mass is $4.33 \times 10^9$ solar masses. Let us estimate the...
accretion rate needed to spin the black hole up to a dimension-
less spin of about 0.5 as an ADAF and in turn determine the time
for that process. The Eddington accretion rate in terms of solar
masses per year (from [38])

\[
dM/dt_{\text{Edd}} = 2.2 \times 10^{-8} M_{\text{BH}} \text{ year}^{-1} \tag{1}
\]

If the black hole entered the ADAF phase with \(4.33 \times 10^9\) sol-
ar masses, its average Eddington accretion rate to build its black
hole to \(6.5 \times 10^9\) solar masses is 119.3 solar masses per year. But
as an ADAF it must accrete below 1.193 solar masses per year. If
we assume slightly below that value at 0.002 times the Eddington
accretion rate, the required buildup time is

\[
T = \frac{M_{\text{acc}}}{(dm/dt)_{\text{avg}}} \tag{2}
\]

where \(M_{\text{acc}} = (6.5 - 4.33) \times 10^9\) solar masses and \((dm/dt)_{\text{avg}} =
2 \times 10^{-3} \times 119.13\) solar masses year\(^{-1}\), which gives 9.1 billion
years.

If, on the other hand, we assume the black hole in M87 cur-
rently has high prograde spin and the mass therefore doubled,
it went from 3.25 billion solar masses to 6.5 billion solar masses
and therefore accreted 3.25 billion solar masses. The average Ed-
dington accretion rate in this case is 107.25 solar masses per year.
At 0.002 times the Eddington accretion rate, the required time to
reach the 6.5 billion solar mass threshold is 15.1 billion years.
Recent estimates of the accretion rate onto the black hole in M87
are orders of magnitude smaller at about \(9 \times 10^{-4}\) solar masses
per year.\(^{[39]}\) This is \(\approx 10^{-5}\) the Eddington rate. General rela-
tivistic magnetohydrodynamics (GRMHD) simulations for the Event
Horizon Telescope Collaboration estimate similar accretion rates
(i.e., \(\approx 2 \times 10^{-5}\) \(dM/dt_{\text{Edd}}\) [40]). For the model to work, the aver-
age accretion rate must be above \(10^{-3}\) \((dM/dt)_{\text{Edd}}\). From the model
perspective, we can identify a decrease in the accretion rate over
time, making the model compatible with these estimates at late
times. Figure 1, in fact, shows that M87 originates in the model
as a powerful FRII quasar, which means its accretion rate was
close to Eddington and that it evolved from a high-excitation ra-
dio galaxy (HERG) to a LERG in a few million years. In other
words, it could have transitioned early to accretion rates on the
order of \(10^{-2}\) \((dM/dt)_{\text{Edd}}\) and lingered in the range \(10^{-2}\) \((dM/dt)_{\text{Edd}}\)
\(> dM/dt > 10^{-3}\) \((dM/dt)_{\text{Edd}}\) for billions of years before dropping
further to accretion rates below \(10^{-4}\) \((dM/dt)_{\text{Edd}}\). Our constraint
is on the average accretion rate, not the instantaneous one. From
the perspective of our evolutionary picture for the accretion rate,
our choice of an average accretion rate of \(2 \times 10^{-4}\) \((dM/dt)_{\text{Edd}}\) ap-
pears reasonable, which in turn tells us that the idea of the black
hole in M87 having a spin that is outside the range \(0.2 < a < 0.5\)
produces tension with the model.

If the black hole in M87 increased by about 1.5 times the origi-
nal black hole mass through ADAF accretion, the original M87
black hole about 9 billion years ago was already near 4.3 billion
solar masses in this model, at the upper end of the black hole mass
scale, which means that in the model we have anti-hierarchical
growth for this system. Both the timescale for evolution into an
FRI ADAF and the original black hole mass of M87 suggest that
it was one of the massive black holes that formed early in the
universe. Although a very high retrograde spin for M87 has not
been ruled out by observations, as mentioned above, high retro-
grade/prograde spin in the gap paradigm is fundamentally con-
tected to jet morphology. Since M87 appears to have a classic FRI
jet, it cannot be a retrograde accreting black hole in that model.

Although this article compares two different paradigms, it
is hoped that analytic and numerical work will eventually con-
verge and signs of this possibility are coming to light. Not only
is much of the physics of black hole accretion still absent in
GRMHD, even with the currently implemented physics, we are
still learning how to simulate accretion around black holes. The
detailed dependence of jet power on the magnetic field strength
threading the horizon, black hole mass, and black hole spin, is
work in progress. While the simulations are now fully three-
dimensional, including radiation remains challenging and the
efficiency of black hole accretion therefore uncertain.\(^{[41]}\) Even
basic processes for the transport of angular momentum may
not operate as thought previously. In fact, magnetic instabi-
lities may contribute to the accretion process, such as in magne-
tically arrested disks where the magnetorotational instability is
marginally suppressed.\(^{[42]}\) Recently, for example, it was discov-
ered that GRMHD simulations were not sufficiently resolved to
appropriately explore dynamo behavior in the accretion flow.\(^{[43]}\)
This is not a second order effect as it is directly related to the
buildup of magnetic flux on the black hole which in turn deter-
mines whether a jet is formed.

With techniques that allow radiative effects to be incorporated
in increasingly realistic ways, recent GRMHD simulations show
that a disk wind may help to collimate the jet. As a result, a new
picture is beginning to emerge from GRMHD which to some de-
gree is parting ways with the basic picture in which thick disks
are required to accelerate and collimate the jet. Instead, their
purpose now seems to be anchored to bringing magnetic flux to the
black hole. This need to drag sufficient magnetic flux to the black
hole has long been recognized as fundamental, with the caveat
that the gap paradigm, by contrast, accomplishes this via the zero
flux boundary condition (i.e., the Reynolds condition) in the gap
region. The prediction is that as more physics is included and
implementation techniques improve, GRMHD simulations will
show the jet efficiency to increases in the counterrotating accre-
tion regime. This higher jet efficiency in retrograde systems is
crucial in producing the time-dependent evolution that has made
the gap paradigm fit so well with observations.
3. Conclusions

Although both spin paradigm and gap paradigm prescribe the black hole in M87 to be in corotation with its accretion disk, we have shown that they span mutually exclusive regions of the spin space, the former involving a very narrow high spin range while the latter a larger but lower spin range. No further constraints emerge in the spin paradigm. In the gap paradigm, on the other hand, super Eddington accretion is not a feature of the model which places additional constraints on the evolution timescale. Because the black hole accretes most of its lifetime as an ADAF, billions of years are required to spin it up into a region where the model allows for the formation of a powerful FRI jet. These constraints strongly favor a very high mass for the original black hole that formed in the last significant merger that produced the M87 galaxy. Spin constraints have now emerged in the gap paradigm for all families of AGN but, whereas for radio quiet quasars/AGN and radio loud quasars/AGN the spin is high but associated with corotating and counterrotating disks, respectively, the powerful FRI radio galaxies appear to fit as corotating ADAF disks with intermediate spin values. In other words, the less massive black holes in radio quasars have the highest spins but in retrograde configurations whereas the most massive black holes in radio galaxies tend to have intermediate prograde accreting black holes. Although the physical reasons for these conclusions are different, they also emerge in the simulations of Bustamante and Springel.\(^{144}\) Current spin estimates in active galactic nuclei include large uncertainties (e.g., [45]) but will provide the needed constraints in the foreseeable future. We conclude that the best hope to rule out both of the theoretical ideas discussed here, or at least produce tension with them, is for the spin value of the M87 black hole to be measured in the 0.5 < a < 0.9 range.

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Conflict of Interest

The author declares no conflict of interest.

Keywords

M87, supermassive black hole