# The Development of the Theory of Black Holes (mid-1960s—mid-1970s)

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## Gravitation Collapse to Black Holes

By 1939, it should have been clear that sufficiently massive bodies must undergo gravitational collapse to black holes:

- In 1931, Chandrasekhar established an upper mass limit for stars in Newtonian gravity supported by electron degeneracy pressure.
- In 1939, Oppenheimer and Volkoff obtained an upper mass limit for bodies at nuclear densities in general relativity. It is clear from the TOV equation that it is more difficult to support a star in general relativity than in Newtonian gravity.

- Also in 1939, Oppenheimer and Snyder analyzed the collapse of a spherical body of pressure-less matter and showed that it results in a Schwarzschild black hole. (The spacetime structure of the resulting black hole is not presented clearly in the paper, but it is clearly stated that the matter collapses to a singularity in a finite proper time and the matter is cut off from the outside world before it reaches the singularity.)

In retrospect, it is astonishing that this extremely important body of work was completely ignored and/or shunned until the late 1950s. For those that did not ignore the work, the prevailing attitude is perhaps best summarized by the following quote from Eddington: “I felt driven to the conclusion that this [Chandrasekhar’s upper mass limit] was almost a *reductio ad absurdum* of the relativistic degeneracy formula. Various accidents may intervene to save the star, but I want more protection than that. I think there should be a law of nature to prevent a star from behaving in this absurd way!” Remnants of this attitude remained strongly present when I started graduate school in 1968 and persisted, to some degree, for decades:

- Aside from general relativists, black holes were not generally taken seriously by “hard core” astrophysicists and physicists until about the mid-1970s. Mention/discussion of black holes before the mid-1970s would engender the kind of reaction that discussion of, e.g., the "multiverse" would get now.

- Until about the mid-1980s, one never spoke about the presence of black holes in astrophysical systems, just "black hole candidates." [Of course, observational evidence for black holes has generally gotten much stronger, but the observational evidence for, e.g., Cygnus X-1 being a black holes was as strong in the early 1970s as it is now.]
- Until about the 1990s, nearly every talk on black holes used the word "exotic" to describe them.

Nevertheless, by the 21st century, black holes have become an important component of mainstream astrophysics and cosmology, as well as playing a central role in fundamental physics, particularly the quest for quantum gravity.

The general theory of black holes was developed in a period of only a decade, from the mid-1960s to the mid-1970s. It stands as one of the most remarkable achievements in the first century of general relativity. I will now review what these developments were, and how they occurred.

# A Major Impetus: Quasars

Quasars at large redshifts were discovered in the early 1960s. Gravitational (as opposed to nuclear) energy was their only plausible energy source, but this would put them close to collapse, and certainly into a regime where general relativistic effects would have to be considered. This raised the issue (in particular, to Penrose) as whether a stage would be generically reached where gravitational collapse to a singularity is inevitable. The first Texas Symposium (1963) clearly played a major role in bringing issues of gravitational collapse to the fore.

# Penrose's Singularity Theorem: "Global Methods"

Penrose introduced the notion of a "trapped surface"—a compact 2-surface, $S$, for which both ingoing and outgoing future-directed null geodesics orthogonal to $S$ are everywhere converging. He then showed (1965) that the presence of a trapped surface inevitably led to a singularity by the following argument:

- The Raychaudhuri equation (together with Einstein's equation and the null energy condition on matter) implies that all of the null geodesics orthogonal to $S$ will have caustics within some finite affine parameter $\lambda_0$.

- If all future-directed null geodesics from $S$ can be extended to at least affine parameter $\lambda_0$, this implies that the boundary of the future of $S$ is compact.
- By contrast, if the spacetime admits a non-compact Cauchy surface, then the boundary of the future of $S$ must be non-compact.

Thus, the only way to avoid a contradiction is for at least one future-directed null geodesic orthogonal to $S$ to be incomplete.

These types of global arguments were further developed over the next 7 years.

# Uniqueness of Stationary Black Holes

The 2-parameter family of Kerr metrics was discovered in 1963. By 1967 it was understood that they described black holes with angular momentum as well as mass.

In 1967, Israel proved that Schwarzschild is the only static, asymptotically flat vacuum solution of Einstein's equation with a regular event horizon; all other solutions have "naked singularities."

It was soon conjectured that the Kerr metrics are the unique stationary black hole solutions to the vacuum Einstein equation. The proof of this conjecture was completed in 1974, but there was already a widespread belief in its validity in the late 1960s, encapsulated in

Wheeler's phrase "black holes have no hair"—they retain a memory only of total mass, $M$, and angular momentum, $J$ (as well as charge, $Q$, if electromagnetic fields are allowed). This means that from the black hole end-state, one cannot tell anything about what formed the black hole apart from $(M, J, Q)$. In particular, laws of baryon or lepton conservation must be "transcended."

It should be noted that it was *not* proven that gravitational collapse must always result in a black hole rather than a naked singularity. A proof (or disproof) of "cosmic censorship" as formulated by Penrose in 1969 remains today one of the most important issues in classical general relativity.

# Energy Extraction

What was undoubtedly one of the most important discoveries in the theory of black holes was published by Penrose in a footnote of a review article on black holes in 1969: Energy can be extracted from a rotating black hole by making the black hole swallow negative energy. (Locally positive energy matter can have negative energy in the "ergoregion" outside of a rotating black hole, where the symmetry corresponding to time translations at infinity becomes spacelike.)

The energy extraction process in Penrose's footnote involved breaking up a particle falling into the ergoregion into a negative energy fragment (which goes into the black hole) and a fragment that returns to infinity with greater energy than the incoming particle. It was soon realized by Zeldovich and Starobinski and by Misner that there is a wave analog of the Penrose process, known as superradiant scattering: If a wave with $0 < \omega < m\Omega_H$ is incident on the black hole, the reflected wave will have greater amplitude and energy than the incident wave.

Neither the Penrose particle process nor superradiant scattering are very effective/efficient at extracting energy from a rotating black hole, but by 1977 it was realized by Blanford and Znajek that efficient energy extraction schemes are possible with a force-free plasma surrounding a rotating black hole (with a magnetic field supplied by an accretion disc). Thus, rotating black holes could easily provide the energy source of quasars.

# Application of Global Methods to Black Holes

Beginning around 1970, Hawking applied to the theory of black holes the global methods machinery that had been developed to prove the singularity theorems. In particular, if the null geodesics generating the event horizon of a black hole were converging anywhere, by deforming a cross-section of the horizon slightly outward, one would obtain a contradiction concerning the boundary of its future similar to the contradiction obtained in the Penrose singularity theorem. In this case, assuming cosmic censorship, the contradiction can only be resolved by not having convergence of the horizon generators. Thus, he obtained the *area theorem*:

The surface area of the event horizon of a black hole can never decrease with time.

The area theorem enabled one to very simply obtain an upper limit to the energy that can be extracted from rotating black holes.

# Black Holes and Thermodynamics

Wheeler was quite comfortable with the laws of baryon and lepton conservation being "transcended" when a black hole is present. But Wheeler was not happy with the idea that the second law of thermodynamics might be violated/transcended by simply throwing matter into a black hole. Under the influence/suggestions of Wheeler, Bekenstein then investigated the possibility that black hole area might be related to entropy. [I recall thinking at the time that I was glad that I had my own, good problems on black holes to work on, and didn't have to try to follow-up on any of Wheeler's flaky ideas.]

In 1973, Bardeen, Carter, and Hawking published a remarkable paper showing that black holes satisfied analogs of all of the laws of thermodynamics, with surface gravity playing the role of temperature. They pointed out that this was only a mathematical analogy; one could not assign a non-zero physical temperature to a black hole.

# Particle Creation

Zeldovich and Starobinski noted the analogy between superradiant scattering and stimulated emission and concluded that there would be an analog of spontaneous emission (i.e., particle creation) in Kerr in the superradiant modes. This was worked out in detail by Unruh in 1974. However, the analysis was done for an "eternal" black hole, which has a "white hole;" initial conditions on the white hole horizon have to be chosen.

In autumn, 1973, Hawking visited Moscow and Zeldovich and Starobinski told him of their Kerr superradiance particle creation claims. Hawking was skeptical, but realized that the calculation could be done with no ambiguities if one considered a black hole formed by gravitational collapse rather than an eternal black hole. When he did the calculation, he found that black holes emit thermally via particle creation, with a temperature proportional to surface gravity. The relationship between black holes and thermodynamics was now complete!

I look forward to the attainment of a deeper understanding of this relationship during the next century of general relativity.