Early Black Hole Development -- a Princeton view

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Research topics evolve

- Schwarzschild metric
  - From “What what becomes of a large burnt-out star?”
  - To “How are (spherical) black holes formed, and what role do they play in astrophysics?”
- Kerr metric
  - From “What material object could have the Kerr metric as its exterior spacetime?
  - To “What is the role of spinning black holes in astrophysics?”

Research Motivations Vary

- Mathematical curiosity: What variety of solutions do the Einstein equations allow? and how are they to be interpreted?
- Observational pressure: What has been, or might be, observed that could require strong gravitational fields for an explanation?
- The 1963 Texas Symposium on Relativistic Astrophysics was where these two approaches met each other.

Interpreting Schwarzschild

- The Schwarzschild interior metric (1916b,constant density sphere) gives an odd relationship: Maximum mass proportional to (density)$^{-1/2}$.
  - Did anyone care? When?
- Oppenheimer and Volkoff 1939 found a limiting mass (similar to Chandrasekhar's white dwarf Newtonian gravity limit) for a cold neutron gas using Schwarzschild coordinates.

Interpreting Schwarzschild

- Eddington 1924 showed by a coordinate transformation from the usual Schwarzschild spherical coordinates that, in spherical symmetry, the Whitehead and the Einstein threories of gravity give identical results for planetary orbits.
  – He paid no attention to the r=2M region which would need a different metric as it lay within the Sun.

Interpreting Schwarzschild

- Oppenheimer and Snyder 1939, followed the simplest model of a collapsing “star”: spherical symmetry and zero pressure gradients. Their conclusion: “Continued Gravitational Contraction”.
  - The stellar matter quickly shrinks to zero size and infinite density.
  - Radiation from the stellar surface is quickly quenched by the infinite redshift near r=2m, and the visible collapse slows without reaching r=2m.

Wheeler updates O-V

- Harrison, Wakano, Wheeler -- Solvay meeting 1958, report an updated Oppenheimer-Volkov study.
  - PR: Real physicists can use General Relativity
  - JAW motivation: perhaps, as in the ultraviolet catastrophe (Raleigh-Jeans law) for black body radiation, a predicted singularity would be a clue about new micro-physics.

Finkelstein

- Finkelstein's "unidirectional membrane" at r=2m in the Schwarzschild solution was a turning point for physics leading to black holes. (January 1958)
  - He had no astrophysical concerns, only mathematical curiositry
  - Misner (spring 1957) provided Finkelstein with the tools to see what is now called the BH horizon

Kruskal

- Kruskal's paper (submitted 31 Dec. 1959) was written by Wheeler after Misner showed him the Finkelstein result. It was first seen by Kruskal in galley proofs, but the coordinates were sketched informally much earlier to Wheeler.
  - The Wheeler written paper emphasizes wormholes, not astrophysical black holes
  - These coordinates are often easier to use than Finkelstein's, as the light cones are at fixed angles on the page.

Beckedorff

- Having heard of Oppenheimer-Snyder from Sam Treiman, Misner recruited a math undergraduate to carry out a new description of the O-S result using the Kruskal metric outside the infalling matter. (Spring 1962)
- This Princeton senior thesis provided, I think, the first description of the empty space outside the infalling matter at, and after, its crossing r=2m.

Cornell Bondi-Gold "Time"

- Misner presented the Beckedorff calculations he designed to a small group in transcripted proceedings. May 31- June 1, 1963. See http://hdl.handle.net/1903/4280.
- This picture allows one to see the (as yet un-named) black hole as a persistent object no longer tied to its history of formation.
- The 22 attendees included Chandrasekhar Feynman, Morrison, Penrose, Rindler, Robinson, Salpeter, Schiff, Sciama, Wheeler

O-S with Kruskal exterior

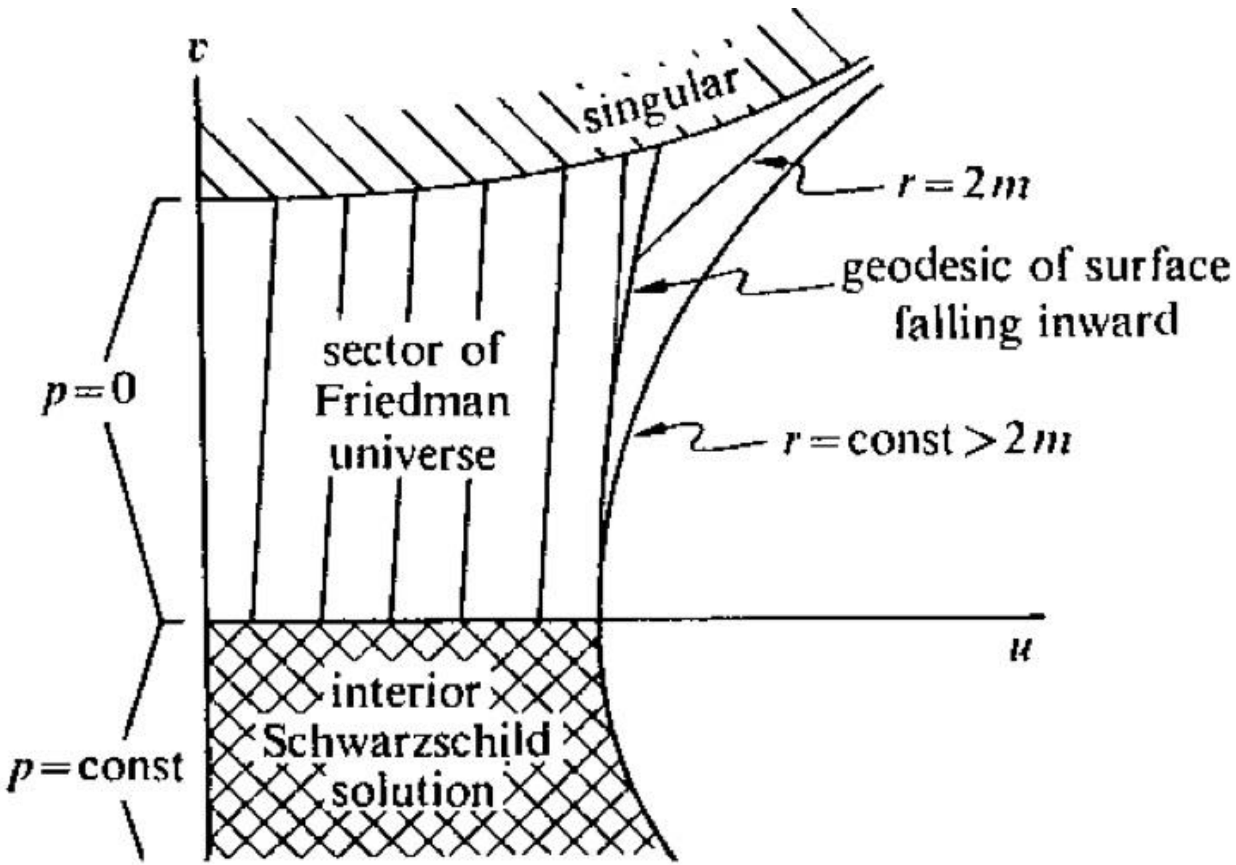

FIGURE VI-7

O-S with Kruskal exterior

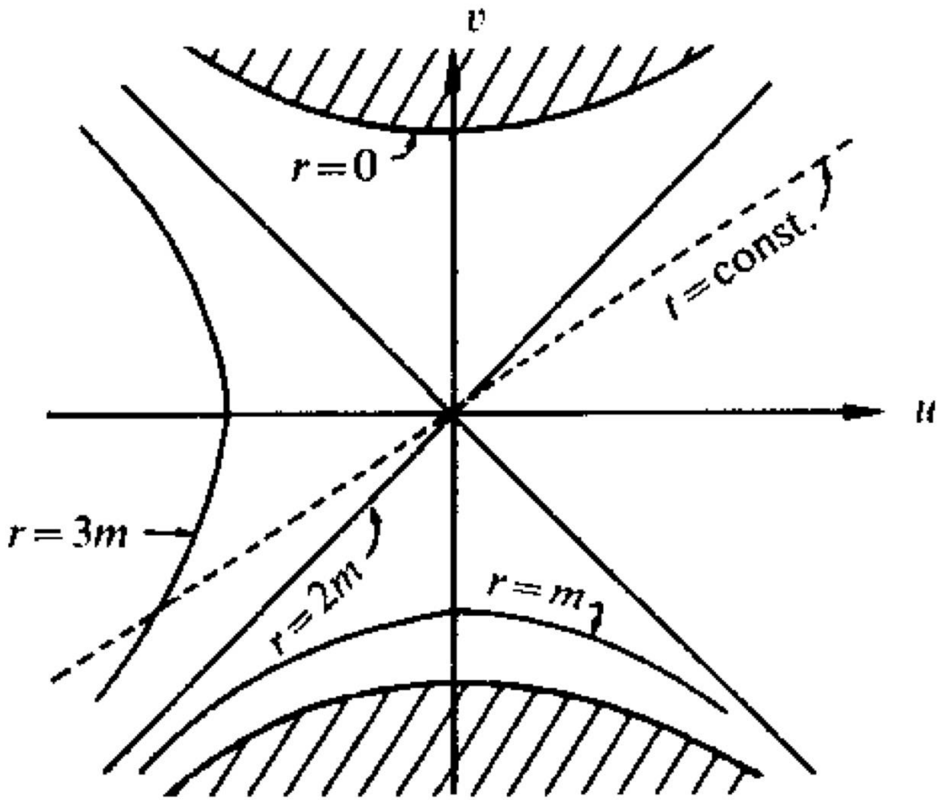

FIGURE VI-4

O-S with Kruskal exterior

Now redraw this so that the beginning of the collapse (here at $v = 0$) is plotted as a large negative value of t, while keeping r constant. But r is a function of $(u^2 - v^2)$ only.

So points in the drawing get shifted along hyperbolas as the time t assigned to an event is made more negative.

All matter filled regions are pushed below the $v = -u$ null hypersurface.

Supernovae give BHs ?

- Colgate, May, and White at Livermore (endorsed by Misner & Sharp) explored collapse more realistic than O-S free fall.
- Computer models of spherically symmetric collapse explore whether it can produce supernovae
- And whether an horizon can form in some cases. (June-July 1964 at Livermore)

Stability of Schwarzschild

- Among my 1963 students at Maryland were Edelstein, Vishveshwara, and Hernandez.
- Edelstein and Vishu were given Ph.D. projects based on Regge-Wheeler (1957) perturbations of Schwarzschild, but now with the Finkelstein/Kruskal view of r=2m to set boundary conditions.
- Vishu obtained now believable results giving stability
- Radiation from an orbiting test particle lost.

Penrose PRL: singularities

- The Penrose 1965 PRL with a theorem about the necessity of singularities in plausible gravitational collapse situations was a bomb-shell.
- The fate of infalling matter was now no longer evaded by excessively idealized models of collapse.
  - Wheeler could hope still more fervently that study of the singularity would give clues to better micro-physics.

The Kerr metric

- The Kerr metric (1963, just before the Texas meeting) also got lots of attention.
- Neither the Kerr paper, nor most readers, tied it to a black hole idea.
- My student Hernandez was set the problem of finding a lump of matter whose exterior would be the Kerr metric.

Negative Energy

- Vishu, studying geodesics in the Kerr metric, found that some geodesics outside the horizon had negative energy, but don't appear outside a small radius.
- Neither he nor I had the creativity to imagine that a particle could decay into one part in a negative energy orbit, and the other in an orbit with an upgraded energy.
- The Penrose idea showed that Kerr metrics were objects with lots of free energy!

Change to BH focus

When, in different places, did the center of attention change from the singularity to the BH?

A Black Hole came to denote an astrophysical object with an horizon whose external spacetime was dominated by gravity where the behavior of matter on a dynamical time scale had little gravitational effect, and where the matter that collapsed to form the BH has lost influence on the physics in view.

Change to BH focus

- Israel remembers from his London talk ('66 or '67) about the Schwarzschild uniqueness of static horizons that "it is to Misner that the credit is due for the first apprehension of the 'no-hair conjecture' with its correct dynamical interpretation"
- Penrose's insight that the rotational energy of a Kerr metric could be tapped for astrophysical use was important in widely promoting the Kerr metric to BH status.

The Carter Constant

- Although equatorial geodesics were adequate for discovering (Vishu) the negative energy orbits outside the Kerr horizon, and for Penrose to explain how to use them, full mastery of dynamics in Kerr spacetime needed the Carter constant.
- Misner contributed to its discovery by showing Carter an example and Hamiltonian tools to search for it: the fourth constant for charges moving in an electric dipole field.

Shift in "Themata"

- Although not phrased that way 50 years ago, one can now see a thematic change occuring:
  - Cf. Gerald Holton on "Themata": proposals for what would constitute a satisfying understanding of Nature such as atomism vs. the continuum.
  - The "singularity" vs. "BH" emphases are an often ignored contrast between "ultimate reductionism" vs. "emergent theories" (cf. Philip Anderson).
  - The BH as an important, independent object "emerges" from GR; but it is not built from the ur-atom (ultimate underlying microstructure).

CWM as Kerr bystander

- The Kerr PRL gave an exciting new GR solution, but left mysterious the pathway to it.
- The only hint there was a reference to the “NUT” paper giving in the same class a solution I studied and published in the same JMP issue as NUT.
- Thus when, 40 years later, I was asked about this I turned to A. Thompson who, with Kerr, is thanked by NUT for correcting errors in the Newman-Penrose paper.

CWM as Kerr bystander

- Kerr and Thompson were office mates in Austin TX at the time of the Kerr metric PRL, and Thompson was accessible by phone.
- He and Kerr had studied a preprint of the NUT paper (as had I, since my reaction to it appeared directly following the NUT paper in JMP)
- Thompson remembered finding no algebra errors in the NUT paper, while Kerr was sure there should be a rotating solution.

CWM as Kerr bystander

- Thompson described Kerr as working intensely for weeks (before a NY meeting prior to which Kerr described his solution to a Stevens meeting).
- They, A.T. and R.K., had found errors, not in the NUT paper but in the N-P paper on which it was based.
- Kerr could see these errors by comparing to a parallel (to N-P) null tetrad scheme he and Goldberg had developed.

CWM as Kerr bystander

- My conclusion was that
  - The NUT paper provided the impetus to search for a rotating metric among algebraically special solutions.
  - These could be found using N-P spin coefficients only after numerous errors had been recognized and repaired.
  - They were likely found by Kerr using extensions of the Goldberg-Kerr methods (which also helped locate N-P errors).

Rapid development

- Following the 1963 Texas meeting (as a marker) many important advances in understanding Black Holes developed
  - Penrose singularity theorems
  - Israel uniqueness of Schwarzschild static horizon
  - Perturbation technology improved (Teukolsky) over Regge-Wheeler
  - Linear perturbations of Kerr completed
  - BH thermodynamics (BH entropy, temp)
- Vast new astrophysical obs'n and theory

My proudest BH work

- Enabling and advertising the Finkelstein causality picture (Schwarzschild horizon)
- Redoing the O-S collapse (with Beckedorff) to include the horizon and the empty spacetime inside it
- Focusing on the visible endpoint of collapse rather than the endpoint for the lost matter.
- Prodding Carter -- by showing him an example -- to find a needed constant using Hamiltonian methods.

Central Questions

- Explore historically the evolution (in various groups) from fascination with intriguing metrics to the exploration of their existence in Nature and the means by which they get produced.
- How overattention to the reductionist evaluation of progress in physics could distract from recognizing “emergent” areas as deeply insightful views of Nature.