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Old/Past/Ancient/Historic Frontiers in Black Hole Astrophysics

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Abstract. Basic questions about black holes, some of which are fairly old, include (1) What is a black hole? (2) Do black holes exist? And the answer to this depends a good deal on the answer to (1), (3) Where, when, why, and how have they formed? and (4) What are they good for? Here I attempt some elaboration of the questions and partial answers, noting that general relativity is required to described some of the phenomena, while dear old Isaac Newton is OK for others.

Keywords. black hole, general relativity, horizon, gravitational redshift, binary stars, quasars, gamma-ray bursts, gravitational radiation, advection, singularity

1. Introduction

The phrase “black hole” in its modern meaning first appeared in print more than 60 years ago (Ewing 1964). Bartusiak (2015) has chased the words back to their Princeton pairing and popularization by Robert Dicke and John Wheeler from 1963 onward. Yes, the Black Hole of Calcutta 1756 event is probably part of the story, and Priya Natarajan (Natarajan 2016) tells us about it (as well as providing an Indian point of view on the zodiac and creation myths). These myths are probably not part of our story, unless you want to consider our universe coming out of a white hole before the epoch of inflation.

The best early description I heard of the phenomenon came in spring 1963 (when there were no black hole theorists by that name and even neutron stars were hardly part of the universe) from the late Thornton Leigh Page (whose father, Leigh Page, was (also) a distinguished physicist) in a UCLA course on stellar evolution. ”It folds” he said, ”a blanket of space-time around itself, and quietly goes to sleep.” He thought that these sleepers and neutron stars were more likely end points for massive star evolution than white dwarfs, which he described as elephants being required to turn into white mice. Elephant color not specified.

It was this folding and sleeping to which Eddington (1926) (p. 6) objected , writing, ”the mass would produce so much curvature of the space-time metric that space would close up around the star, leaving us outside (i.e. nowhere).” Other sorts of objections will turn up as we proceed. On creation ”ex nihilo” and the alternatives, see Leeming & Leeming (1984).

2. What is a black hole?

The arithmetic here is particularly easy, because the Newtonian expression for escape velocity = speed of light gives you the same answer as the relativistic expression with $(1-2GM/Rc^2)^{\frac{1}{2}}$ downstairs, $R = 2GM/c^2$. This brings us to the oldest, simplest definition.

Something with $R \lesssim$ gravitational radius. The recent custom of beginning discussions of black holes with a brief historical introduction (including this one) has made the names of John Michell and Pierre-Simon de Laplace more familiar in this context today than they were a few decades ago. Each wrote (Michell 1784, Laplace 1795) roughly the same thing, that a body with the density of Earth or Sun and a size comparable with the diameter of Earth's orbit would have an escape velocity greater than or equal to the speed of light, and so "all light … would be made to return towards it by its own proper gravity" (Michell), or "il est donc possible que les plus grands corps lumineux de l'univers, soient par cela même, invisibles." (Laplace).

Laplace is the sort of person who has whole books written about him (Gillispie 1997, the same chap who edited the entire first edition of the *Dictionary of Scientific Biography*), though the deep question of why he left his grands corps out of later editions of his book remains unanswered. Michell remains less celebrated, and it seems (McCormmach 2012) that no portrait of him survives. He wrote for a journal that did not include abstracts, which presumably accounts for his title "On the Means of Discovering the Distance, Magnitude, &c. of the Fixed Stars, in consequence of the Diminution of the Velocity of their Light, in case such a Diminution should be found to take place in any of them, and such other Data should be procured from Observations, as would be farther necessary for that Purpose. By the Rev. John Michell, B.D.F.R.S. In a Letter to Henry Cavendish, Esq. F.R.S. and A.S." The B.D. was bachelor of divinity and he was elected FRS for his work on propagation of earthquake waves. The lower case letter s's (except at the ends of words) are stretched out to look like f's with the cross piece missing.

Before moving on to general relativity, let's check that Newton plus a particle theory of light is enough to estimate small gravitational redshifts. A test mass m leaves a large body (mass M, size R) with initial kinetic energy $\frac{1}{2}mv^2 = \frac{1}{2}mc^2$. It arrives at infinity having gained potential energy from $-GMm/R$ to 0, so

$$\frac{1}{2}mv^2 = \frac{1}{2}mc^2 - \frac{GMm}{R},\; v^2 = c^2 - \frac{2GM}{R},\; \frac{v}{c} = \left(1 - \frac{2GM}{Rc^2}\right)^{\frac{1}{2}} \tag{2.1}$$

which is approximately $1 - GM/Rc^2$. Put in properties of a white dwarf $M = 1.5 \cdot 10^{33}$ g, $R = 10^9$ cm, G and c in cgs units to find:

$$\frac{GM}{Rc^2} \approx 1.5 \cdot 10^{-4} \text{ or } \Delta V \approx (1.5 \cdot 10^{-4})(3 \cdot 10^5 \text{ km/s}) \tag{2.2}$$

or $\Delta V \approx 45$ km/s, which is what we see.

Something with a Horizon. This brings us to Einstein and GR, with his four classic papers all submitted on Thursdays (Gutfreund & Renn 2015), and the shortest textbook ever, that by Weber (1961). The first exact solution to the field equations came from Karl Schwarzschild (1916), submitted by Einstein (also on Thursdays), because Karl himself had volunteered for active duty with the German forces in WWI . He died that same year; perhaps less well known is that a number of other classic GR papers date from 1916-19, some written from the trenches. Astrophysically, the important things about horizons are that any material or radiation that crosses them going inward cannot get out (which happens quickly for an observer riding with the infall), but that looking from outside, the infall goes slower and slower, the information about it arrives more and more redshifted, and the external observer thinks the process takes forever. Kerr black holes (Kerr 1965, though the talk was given in 1963) are characterized by angular momentum as well as mass, also have horizons, but also have ergospheres, from which one can extract the portion of the apparent mass-energy that is associated with the rotation (Penrose 1969, Blandford & Znajek 1977, discovery and application respectively).

Stuff disappears at the horizon. Stuff means either matter or information in this context, and the arguments have been more complex and aggressive about the information. Whether entropy can disappear is even more contentious. The case where energy is carried down the tubes is called advection-dominated-accretion.

Information/matter/entropy hangs up at/around the horizon. This is the membrane paradigm, usually associated with Kip S. Thorne, though he credits others (Thorne 1994) for pioneering the idea. The important associated idea is that, if stuff hangs up just outside $R = 2GM/c^2$ (or the Kerr equivalent), then it probably comes back out in due course, with information (who was that hadron I saw you with last night?) and entropy intact. Modern black holes (well, perhaps modern theories) can also act like conductors, permitting the support of magnetic fields in their neighbourhood, with which, in turn, jets can be collimated and other wondrous things occur.

Strange things happen inside. First, if you look at the line element, space and time exchange their properties, and you can traverse a space-like interval but not a time-like interval. Perhaps also your wrist watch turns into a ruler and your meter stick into a chronometer, but I haven't checked. Second, physical objects get torn, shredded, chaotically mixed, and destroyed. Third, at the center there is a singularity (a point for the non-rotating Schwarzschild case, a small circle for the more realistic Kerr case). A good, modern GR textbook like Hartle (2003) indexes such matters under "Kerr geometry." Thorne (1994) devoted, appropriately, chapter 13 to "Inside Black Holes." And you will find some discussion of the issues in volumes at many levels of technicality (Begelman & Rees 2010, Scharf 2012, Bartusiak op. cit., Thorne op. cit., Hawking & Israel 1987, Hartle op. cit. and so forth). A singularity sounds bad enough when you say just that density and space-time curvature will be infinite there. Even worse, world lines end there. Physics (at least general relativity) loses all predictive power, and many physicists have said that quantum gravity must prevent anything of the sort from happening. The key "singularities happen" paper is Hawking and Penrose (1970), with credit also due to Werner Israel and George Ellis on related topics. In any case, a general relativistic expanding universe must have a singularity in its past, and a body that collapses inside its gravitational (Schwarzschild, Kerr) radius has a singularity in its future, no matter how asymmetric, chaotic, or messy the collapse is.

3. Do Black Holes exist?

This is clearly the key question from an astrophysical point of view! The answer will depend somewhat on the definition we choose from Section 1, but in any case one can imagine three pieces: can they form? or if not, could they have existed from before or during the Big Bang? and do they persist? Let's give the theorists the first word, before going on to what astronomical observations might tell us.

J. Robert Oppenheimer, about whom many things can be said that are not relevant to our story, having dealt with neutron stars in a collaboration with George Volkoff (Oppenheimer & Volkoff 1939) sat down (well one's image has him pacing around continuously) with Hartland Snyder to calculate "On continued gravitational contraction" (Oppenheimer & Snyder 1939). Published the day World War II broke out, this so annoyed Einstein that he rushed into print (Einstein 1939) in an attempt to show that, at least for a cluster of mass points in circular orbits, angular momentum would forever prevent the collapse. This was sufficiently wrong that it appears only as part of an exercise for the student in Misner, Thorne & Wheeler (1971).

Physicists who had been young when WWII broke out contributed to bomb development, radar, and many other things, and some came back to establish relativity groups.

A younger generation (now not so young) settled down to establish the reality of gravitational collapse and singularities. Penrose (1965), less than 3 pages long was crucial. Lifshitz & Khalatnikov (1961) thought they had proven that a sufficiently disordered system could not yield a singularity. Thorne (1994) (p. 465 ff) tells the story of how they changed their minds.

So, collapse will make singularities with black holes and horizons around them. What about primordial black holes? The sub-stellar mass black holes suggested by Hawking (1971) must be of that type, since there is no pressure strong enough to form them now. We currently have no evidence for these, nor of other much more massive ones that could go back before the beginning (but need not), and could be relevant to LIGO events (but need not).

As for persistence, a speaker at GR21 in New York in July said firmly that a Kerr black hole will eventually spin down to a Schwarzschild black hole, but that the Schwarzschild one was forever, because the time scale for evaporation by Hawking radiation would always exceed the time scale for growth by capture of CMB photons, for some BH mass above some calculable limit. Unfortunately, I have been unable to identify the speaker from the conference program and pages of notes I took at the time.

Which brings us to the observations, sometimes filtered through theoretical minds.

Sizes close to gravitational radii. Michell (1784) thought one might detect his dark stars by their gravitational pull on luminous bodies, and Zwicky (1937) supposed that gravitational lensing would reveal all forms of mass (both correct). And then, as previously noted, there was a war, and GR crept gradually back into prominance after a long latency period (Blum *et al.* 2015).

Observational radio and X-ray astronomy leaped ahead of theory for a while, so that we pick up in 1964 with Salpeter (1964) and Zeldovich & Novikov(1964) proposing that the energy source for the recently-discovered quasi-stellar radio sources (now quasars, even the radio-silent ones) might be accretion onto a central very compact mass. An early worry was that spherically-symmetric accretion would take all the carefully-accumulated potential energy down the tubes with the gas, and so accretion disks were invented. Over the next 20 years, something of the sort became the standard model for active galactic nuclei (Rees 1984).

Close binary stars slopped gas back and forth starting at about the same time (Hoyle 1964, Paczyński 1971), and Zeldovich & Guseinov (1965) soon set out to look for cases where the recipient was a collapsed or frozen star; neutron stars were added to the search space after the discovery of pulsars. No, they didn't find any, nor did Trimble & Thorne (1969) with a larger catalogue to examine. But the method was right – check for X-ray emission from systems where the optically-invisible component was too massive to be a white dwarf. That HDE 226868 was not in the Batten (1967) catalogue of spectroscopic binary orbits is a sad story for another time. But it was the optical identification for Cyg X-1, on which I wrote (Trimble *et al.* 1973) the last fundamentally wrong paper. And since then, the best mass estimate for the accretor has gradually crept up from about $6M_\odot$ to $10M_\odot$ or more. Not a white dwarf; not a neutron star.

Horizons. On the assumption that accretors of more than about $4M_\odot$ must be BHs, one can then say that, in X-ray binaries, they never display the sorts of X-ray bursts (called Type l) associated with stuff hitting a neutron star surface. Spectral signatures are not reliable, and BHXRBs sometimes show quasi-periodic oscillations not so very different from the NSXRBs, but there is never a signature of a constant rotation period. Analysis of eclipses in BHXRBs reveal distortions connected with space-time being dragged around, by angular momenta from about 0.3 to 0.95 of the maximum possible. The assortment of radio installations being called the Event Horizon Telescope should soon record radio waves being bent almost all the way around by the black holes in our own Sgr A* and M87.

Energy disappearing. Having invented accretion disks to make sure that the energy released by infall to black holes came out as radiation (Shakura & Sunyaev 1973), the community then had to back off and deal with BH emitters of X-rays at levels very considerably below their Eddington luminosities. At least three excuses are possible. First, you may see material coming in at a distance, but it all gets turned around into outflow or collapsed into stars. Second, there truly is very little around to accrete (until an AGN-BH tears up another star or an XRB BH ruffles its disk). Or, third, secreting gas is carrying with it a great deal of the thermal energy. This is called advection-dominated accretion (ADA). Narayan *et al.* (1998) is a very nice status report. The clearest cases they discuss are, for XRBs, A00620-00, V404 Cyg, and Nova Muscae 1991 and, for AGNs Sgr A*, M87, and NGC 4258 (the one with the maser disk providing a good measurement of the BH mass). The three BHXRBs have flared up near to the Eddington luminosities and fallen back to 10^{-4} or less, with quiescent accretion rates proportionally depleted. The AGN BHs are even fainter, though at least for SgrA*, the ADA explanation (Fabian & Rees (1995), Rees (1982)) may not be the likeliest explanation for faintness now and much higher luminosity within the past 100 years (Ponti *et al.* 2014). The main point made by Narayan *et al.*, is that the ADA hypothesis provides much better fits to observed spectra than does a standard accretion disk. The same claim is made for the X-ray light curve of Nova Muscae 1991 (data from Ebisawa *et al.* 1994), but look for yourself, before you endorse or confute my skepticism.

Exciting happenings just outside or inside the horizon. Black hole entropy, thermodynamics, and radiation are old enough to count as history (Bekenstein 1972, Hawking 1974), but there do not seem be any very relevant observations, except that one can say either the universe is not bound by low-mass primordial black hole, Hawking radiation doesn't happen, or both. Thorne (1994) has a whole chapter (Ch. 13) on ”inside”, and Amos Ori (Ori 1991, Ori 1992) has attempted to look inside relatively realistic geometries. But I learned my lesson from Penrose (1962), ”Don't go there!”. And indeed, although quite a number of our graduate students seem to have descended past horizons, none of them has ever submitted a thesis.

4. What are they good for?

This is just a list with comments, because all suggestions to date remain viable for some set of parameters.

- Dark Stars, as suggested by Michell and Leverrier, although theirs would have had masses near $10^8 M_\odot$.
- Galactic nuclei, for a very large fraction of galaxies, though most are not active at present, because of starvation, advection dominated accretion, or masses, hence horizon radii, too large for tidal disruption of captured stars.
- Gamma ray bursts, if not when PBHs boil away, then more common sorts of GRBs associated with collapses of rapidly-rotating cores of massive stars and/or mergers of neutron star pairs.
- Dark matter, in moderate amounts formed from material that was previously baryonic, but must have taken matter out of the baryon inventory before BB nucleosynthesis if BHs are to be the dominant dark stuff.
- Bursts of gravitational waves, both at formation and when merging in binary star systems.

The last item led directly to a bunch of photographs (from about 1965 to 1985) showing the first generations of detectors for gravitational radiation and Joseph Weber who built them, in company with Howard Laster and Gart Westerhout (former directors of physics and astronomy at the University of Maryland); Darrell Gretz and another of the technician/programmers who helped operate those early detectors; Nathan Rosen (of Einstein *et al.* 1935); who later in his career (played out in Israel) came to doubt not only gravitational waves but GR in general; Ron Drever (a major contributor to the design and construction of LIGO); Fang LiZhi; distinguished theorist David Finklestein; and yours truly.

5. Conclusion

There is, of course, no end to "history", it merely hands over to "current events" (as at least one designer of time machines discovered to his distress), but a nice end-point for my generation is the flowchart, drawn by Roger F. Griffin, to accompany the text of Martin J. Rees's (1978) Halley Lecture. It also appears in the more accessible Rees (1984), and in full, glorious color in Begelman & Rees (2010). The key point is that it is really quite difficult to avoid forming a black hole sooner or later, when gravity is the dominant force.

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