BOOKS: ASTROPHYSICS

Black Hole Horizons

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Subrahmanyan Chandrasekhar (Chandra) died in August 1995, ending a career that began in 1931 with the stunning discovery that there is an upper mass limit for White Dwarf stars. For such stars with masses over 1.4 times that of the sun, gravitational forces overcome the quantum mechanical pressure of degenerate electrons. Today we blithely say that stars exceeding the Chandrasekhar mass collapse to neutron stars—or even further, to black holes. In 1931 the renowned astrophysicist A. S. Eddington (whom Chandra had come to Britain to work with) remarked "that this was almost a reducto 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!" (Quoted by Chandra's widow, Lalitha Chandrasekhar, p. 274.)

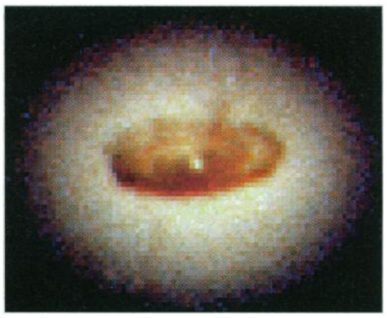
Black Holes and Relativistic Stars
Robert M. Wald, Ed.
University of Chicago Press, Chicago, 1998. 290 pp. $50, £39.95. ISBN 0-226-87034-0.

Although Chandra retained his respect for Eddington, after the controversy he redirected his interests, as he would do repeatedly throughout his life. Indeed, according to Lalitha Chandrasekhar, he believed it was because of Eddington that he worked as he did, moving on after each field was explored. Chandra's approach was to pick a field, consult the seminal references, complete a thorough analysis, and in the end produce a compact, self-contained monograph that set the standard for the field.

Black Holes and Relativistic Stars is based on a December 1996 symposium held in honor of Chandrasekhar (*1*). It follows the symposium's division into sections on classical and astrophysical black holes (an area Chandra was closely interested in), and on black holes as quantum objects (emphasizing their thermodynamical and information theoretical properties). The book ends with written versions of talks Kameshwar Wali (Chandra's biographer) and Lalitha Chandrasekhar gave at the symposium banquet.

Two of the classical and astrophysical papers are very closely related to Chandra's work: Ferrari discusses the perturbation of black holes and extends concepts from Chandra's *Mathematical Theory of Black Holes* to stars. Friedman considers rapidly rotating stars and instabilities due to gravitational radiation. Two others summarize the (nearly) current observational context for black hole studies: Rees reviews astrophysical evidence for black holes (x-ray sources in binary systems and in active galactic nuclei). Thorne discusses the use of gravitational radiation to probe the interaction of condensed objects (neutron stars and black holes) and view the universe out to redshifts of ~1.

Teukolsky's chapter on numerical relativity (numerical solution of Einstein's equations) rounds out the astrophysical contributions. He discusses insights from computer simulations of collapsing matter and black hole collisions. These show the surprising possibility of toroidal black holes and aid the analysis of the geometry of event horizons (the light-like surfaces dividing light rays that reach to infinity from those that do not). Israel instead discusses the internal structure of black holes, concentrating on the stability (or lack thereof) of the Cauchy horizon within black holes that are charged or rotating. This horizon must be crossed in tunneling through (to emerge into "another universe"). Because the studies to date assume symmetries in space-time, a full understanding of black hole interiors and whether we could, in principle, tunnel through a black hole awaits further analysis.



Black hole home. Gas and dust at the center of the nearby elliptical galaxy NGC 4261 (photographed with the Hubble Space Telescope) appear to be falling into a massive black hole.

The remaining classical contribution, by Penrose, consists of a long discussion of cosmic censorship—the idea that in generic gravitational collapses the resulting space-time singularities are hidden from view of distant observers. The formal idea is that of a black hole horizon, which "clothes" the singularity inside the black hole. The picture is that gravity is so strong that those light rays inside the horizon are pulled back toward the singularity. Hence if there is such a horizon, the singularity is clothed. In its broadest sense, cosmic censorship fails. In Newtonian gravity, it is easy to find infinite-density effects (shell crossings) in spherical systems; these persist and are not clothed when one redoes the computation in general relativity. So one must specify a number of conditions to have even a chance of cosmic censorship holding. Thus, Penrose gives a trial formulation of a "principle of *strong cosmic censorship* as the assertion that naked singularities or points at infinity ... do not occur in generic space times, where it is assumed that Einstein's equations hold with some reasonable equation of state for the matter." "Generic" and "reasonable" are left without specific meanings until the appearance of rigorous theorems on cosmic censorship, which will necessarily give precise definitions for them. (Stephen Hawking's recent, widely celebrated concession, forced by M. Choptuik's computations, arose because Hawking failed to specify "generic" when he bet that naked singularities do not exist.) Although Penrose suggests several directions to search for a proof of an appropriately formulated censorship theorem, no one has had even tentative success.

The chapters concerning thermodynamic and quantum aspects of black holes provide a stage for the unresolved debate on recent results in string theory, which in a low energy limit is ten-dimensional (10D) supergravity theory. In such a theory one can construct black holes in a 10D geometry described by a curved metric g_{ab}. A separate limit, the weak coupling limit, admits soliton-like (coherent wave) solutions called D-branes. Horowitz discusses the relationship between these two limits as well as other applications of string theory to the quantum mechanics of black holes. For instance, certain weak coupling states comprised of D-branes can be identified with certain black hole solutions of the low energy limit ("duality"). The entropy of the D-branes (ordinary degrees of freedom in a flat space-time background) can be computed by standard formulae ("mode counting"). In some cases the resulting value agrees with that obtained via Hawking's approach of the duality-related black hole—remarkably, because there is no apparent degree-of-freedom counting for the black hole case.

This observation has led to a surge of activity on string theory. Although 10D supergravity is not directly a theory of gravity for the 4D (space plus time) world we in-

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habit, the coincidence has also raised excitement in the gravitational community. Hawking's article in this volume, however, contains a strong critique of the D-brane computation of the entropy. Hawking finds that correctly including curvature effects changes the boundary behavior of the D-brane, so there is no real conservation of information from early to late times. (The bounding hypersurfaces become null, that is, light-like.) Generic information from the past bounding surface cannot be measured across the future one, and so, Hawking argues, the D-brane entropy calculation fails.

Wald (the volume's editor) provides an elegant introduction to black hole thermodynamics and entropy from the 4D point of view. From this perspective, it is extremely difficult to see any connection with mode counting. Information that falls into the black hole appears to be lost, because what emerges from an evaporating black hole is thermal radiation (by definition, uncorrelated). We cannot recover this information because there are modes inside the horizon that are inaccessible to the outside observer. Hawking's thermal radiation computation is on very solid footing for black holes above the Planck mass, ~10^{-5} gram (*2*). Thus it is unlikely that the information is emitted prior to this "Planck era." Then, if the black hole finally evaporates under Hawking radiation, there is a presumably momentary singularity (a "thunderbolt"), which must be given a quantum gravity description. More importantly, most of the information that fell into the hole appears to have been lost, unless it can escape during the quantum era. It seems impossible that it could escape then, because the Hawking temperature of a 10^{-5}-gram black hole corresponds to a single thermal photon having enough energy to carry away all the remaining 10^{-5} gram mass of the black hole, and one photon cannot carry out all the classical information that fell into the black hole. Hence, either the information disappears (there is a "thunderbolt"), or the evaporation stops roughly at the Planck scale and one can view the information as being stored forever in surviving 10^{-5}-gram "nuggets." These seem to be the only possibilities.

Hartle proposes that we ought to be satisfied with a 4D view of the situation (in which we do not demand that a particular time contains all the information), but that our exterior knowledge must be enhanced by using knowledge from within the black hole (before it evaporated). Sorkin suggests ways in which the information in the black hole can in principle be stored, and discusses why the entropy is proportional to the black hole's surface area rather than to its volume.

The contributors have produced a surprisingly readable and topical volume; still, there is definitely room for a broader survey of work inspired by Chandrasekhar. Wali mentions Chandra's works on Newton's *Principia* and on aesthetics in science, but these are not discussed. Chandra made extensive contributions to stellar astronomy and was for many years the editor of the *Astrophysical Journal.* (Legend has it that he read every submission; from personal experience, I believe this is true.) The position reflected his expertise in all aspects of "classical" astronomy, as well as in the more exotic astrophysics that are the focus of the current volume. So we can hope to see other tributes to Chandra, concentrating on substantially different areas of discourse. If they match the standards of *Black Holes and Relativistic Stars*, they too will be very valuable contributions to the current research literature.

References and Notes

1. J. Glanz, *Science* **275**, 476 (1997).
2. For the Planck mass, the Compton wavelength and horizon radius are equal. The Compton wavelength (referring to quantum-mechanical properties) gets larger as the mass gets smaller, while the horizon radius is proportional to the mass. For black holes smaller than the Planck mass, quantum effects are at least as important as gravitational effects and a correct description requires a still unspecified quantum gravity.

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John Wass

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