Sciama, Dennis William (*b.* Manchester, England, 18 November 1926; *d.* Oxford, England, 19 December 1999), *cosmology, steady state theory, general relativity, astrophysics, quantum gravity.*

Sciama was one of the key figures in the renaissance of cosmology in the 60s, and his contributions spanned a broad array of topics in general relativity, astrophysics, and cosmology. The influence of Sciama's own research, however, has not been as great as the influence on the development of relativity and astrophysics he exerted as an inspiring mentor and research leader. He supervised over 70 doctoral students, many of whom have become leading figures in relativistic astrophysics, and conveyed his enthusiasm for the field to many more through his lucid review articles and popular books.

Sciama spent his early years in Manchester, the younger of two sons in a non-religious Jewish family. Both sides of the family had roots in the Middle East: his paternal great grandfather emigrated to Manchester from Aleppo, Syria, and his mother was born and raised in Cairo. Sciama attended Malvern College, a public boarding school in rural Worcestershire, where he discovered an interest in and aptitude for science and mathematics that lead to a minor scholarship at Trinity College, Cambridge.

Sciama went up to Trinity in 1944, where he studied mathematics for one year before switching to the Natural Sciences tripos (focusing on physics) as a condition for a continued wartime deferment. His enrollment in one of Wittgenstein's seminars gives an indication of Sciama's broad interests. Due to mediocre exam results (a lower second) on the B.A. degree, completed in 1947, he could no longer avoid conscription. Thanks to the intervention of the Cambridge physicist Douglas Hartree, most of his two-year stint in the army was devoted to research in solid state physics (photoconductive materials, in particular) at the Telecommunications Research Establishment. Reports he wrote on the subject earned him a second chance in academia, and he returned to Trinity in 1949 in an unpaid research position. Initially Sciama planned to write a thesis in statistical mechanics regarding cooperative phenomena under Neville Temperley, but his interests soon shifted to relativity and cosmology. As a result Dirac was assigned to be his advisor, although two young Cambridge fellows, Herman Bondi and Thomas Gold, had much more influence on Sciama's research. Upon completing his thesis Sciama made a bold wager with his father: if he won a fellowship at Trinity he would continue to pursue physics, and if not he would return to the family business in Manchester.

Sciama's thesis focused on the origins of inertia and Mach's principle. Mach's influential criticism of Newton purported to show that the inertia of a given body could be explained in terms of interactions with other bodies without any appeal to "absolute space." Despite the ambiguity of Mach's formulation of these ideas, they were an inspiration for Einstein's theory of general relativity. In 1918 Einstein included Mach's principle, which he formulated as the requirement that the gravitational field is fully determined by the distribution of matter, on a list of three fundamental physical principles of his new theory. However, he eventually realized that his theory did not satisfy Mach's principle so formulated and abandoned the idea. Sciama had the opposite response: he found Mach's principle so appealing that he sought to formulate an alternative gravitational theory in which it holds. His thesis developed a simple theory with a vector potential based on the Machian idea that inertia and gravitation are entirely determined by the distribution of matter. This was intended as a first step toward a fully Machian theory; in the published version, Sciama promised to develop a more sophisticated, relativistic theory with a tensor potential (as in Einstein's theory) in a second paper.

The second paper did not appear until 1969, and it marked a substantial shift in Sciama's approach rather than a completion of the original program. Sciama and his co-authors (his student Peter Waylen and Robert Gilman, a student of John Wheeler) gave an integral formulation of Einstein's theory rather than developing an alternative Machian theory. The gravitational field at a point was expressed as an integral over physical sources in the surrounding volume plus a boundary term. Mach's principle could then be formulated as a selection criteria for acceptable solutions; roughly, in the limit as the volume under consideration grows to include the entire universe, the boundary term should vanish, so that the gravitational field is entirely determined by the distribution of matter. Derek Raine, a later student of Sciama's, further refined the definition of Mach's principle in this approach by showing how to handle this rather subtle limit. This approach differs from that taken by other advocates of Mach's principle; in particular, Julian Barbour (with various collaborators) has given a Machian reformulation of mechanics based on a "best-matching procedure," a way of defining spatial position and motion intrinsically without appeal to background geometry. Mach's principle continues to be controversial, partly due to the lack of consensus regarding its meaning, but Sciama and his collaborators clarified one prominent approach.

Sciama's interest in Mach's principle reflected the philosophical orientation of his mentors Bondi and Gold. Along with their slightly older colleague Fred Hoyle, Bondi and Gold introduced the steady state theory in 1948. Unlike the standard "big bang" models of relativistic cosmology, which describe a universe that evolves with time, the steady state theory was based on the idea that the global properties of the universe do not vary with time. Bondi and Gold defended the theory on explicitly methodological grounds: on their view, the steady state theory was the only possible scientific cosmology. A theory that allowed for variation of the global properties of the universe could not rule out concomitant variation of local physical laws, hence undercutting any attempt to extrapolate physical laws that hold at present to earlier epochs. For Bondi and Gold as well as Sciama, Mach's principle exemplified "interaction" between global properties and local laws, since it holds that the global distribution of matter determines the local inertial properties of a body. In his vector theory of gravity, Sciama derived a relation between the gravitational constant, the average mass density of the universe, and Hubble's constant that illustrated such interconnections between parameters appearing in physical laws (the gravitational constant) and global properties of the universe (Hubble's constant and average density). Sciama was clearly fascinated with global-to-local connections of this kind, which he made the focus of his lucid popular book *The Unity of the Universe* (1959).

Until 1965 Sciama was actively involved in developing and defending the steady state theory. With Bondi and Gold he wrote a paper aptly criticizing the Stebbins-Whitford effect, which was initially thought to indicate a correlation between the age and distance of galaxies incompatible with the steady state theory, but was later withdrawn. His most important contribution was an ingenious account of galaxy formation published in 1955. At the time there were competing accounts of how the transition from a homogeneous early state to a clumpy state with galaxies and other structures could occur in the big bang models. In the steady state theory, the problem was to maintain an unchanging average density of galaxies as the universe expands. Sciama argued that new galaxies would be created in the gravitational "wake" of existing galaxies, and the requirement of maintaining "equilibrium" put tight constraints on the theory. The theory led to a variety of results in rough agreement with observations, and it was in many ways superior to the speculative accounts of galaxy formation then available for the big bang models.

In the early 60s Sciama's focus shifted to assessing the implications of radio astronomy for the steady state theory. Martin Ryle and others had measured the relationship between the number of radio sources and flux density in the 2C and 3C surveys. The steady state theory made a very specific prediction that was apparently incompatible with these results, although their interpretation results was not without controversy. Sciama proposed that many of the radio sources were galactic rather than extragalactic in nature, and that the apparent discrepancy resulted from a local deficit of galactic sources. The discovery of quasars in 1963 made the situation more difficult for advocates of the steady state theory. Initially Sciama extended his idea of a mixed population to quasars: if some quasars are local rather than extragalactic, then it would again be possible to save the theory. However, unlike Geoffrey Burbidge and Hoyle, Sciama accepted that quasars with measurable redshifts were at cosmological distances rather than within the galaxy. Sciama and his student Martin Rees then showed that the redshift – flux density relation for 35 quasars was clearly incompatible with the steady state theory. This result led Sciama to abandon the steady state theory, although he clearly regretted the demise of a theory he found philosophically and aesthetically appealing. Sciama's conversion was complete; the steady state theory merited only a brief dismissal in his book *Modern Cosmology* (1971), whereas the big bang models took center stage.

Sciama also explored Einstein's general relativity throughout the 50s and 60s. Following his Trinity fellowship, which was interspersed with two years abroad at Princeton and Harvard, Sciama briefly held posts at King's College, London (funded by Bondi's US Air Force research grant) and Cornell (on an invitation from Gold). He returned to Cambridge in 1961 as a lecturer and later fellow in Peterhouse. Before his return to Cambridge he discovered that spin angular momentum could be introduced as a source of the gravitational field by modifying Einstein's theory to allow for non-zero torsion and emphasized the formal analogies between this approach and a geometrical treatment of electromagnetism. The resulting theory, called the Einstein-Cartan-Sciama-Kibble theory to acknowledge its sources in work of Einstein and Elie Cartan and its independent discovery by Thomas Kibble, led to further research based on the hope that it would be easier to combine this generalization of general relativity with other field theories.

At Cambridge Sciama inspired a group of exceptional students to study the then mostly neglected subject of general relativity. Sciama's research group in the Department of Applied Mathematics and Theoretical physics was one of the world's best relativity groups, comparable to those led by Yakov Zel'dovich in Moscow, and John Wheeler at Princeton. Sciama's students, including George Ellis, Stephen Hawking, and Brandon Carter, played an active part in the renaissance of relativity in the 60s. One of the main contributors to this dramatic upswing in productive research was Roger Penrose; although Penrose was never a student of Sciama's, Sciama inspired him to change fields from mathematics to physics. Penrose introduced mathematical techniques that allowed theorists to study stellar collapse and cosmology without relying on specific, artificially simple solutions. One of his most important results was a proof that a collapsing star with sufficient mass will inevitably lead to a physical singularity. Stephen Hawking extended Penrose's techniques to cosmology, and he proved that cosmological models satisfying a number of plausible requirements must likewise include an initial singularity. George Ellis and Hawking wrote the definitive monograph on the subject, *The Large Scale Structure of Space-Time*, which concisely presented the Hawking-Penrose singularity theorems and the new mathematical techniques. Sciama encouraged Brandon Carter to study the Kerr solution, which describes a spinning black hole. Carter discovered a number of the properties of the solution, and contributed to proving the black hole uniqueness theorems. Although Sciama himself did not actively contribute to this line of research, his students clearly benefited from his support, guidance, and ability to identify important problems.

Sciama's research interests also extended into a variety of topics in observational astronomy and astrophysics. He continued research regarding quasars and other observational results that he had initiated as an advocate of the steady state theory. After abandoning that theory, he turned to detailed studies of the big bang models, focusing on the interaction of matter and radiation in the expanding universe, the formation of galaxies via gravitational clumping, and other topics. He advised a number of students in astrophysics, including most prominently Martin Rees. With Rees he discovered that time-variation in the gravitational potential of a lump of matter would produce a characteristic temperature variation in radiation passing through the region, which is called the Rees-Sciama effect. Sciama's masterful review articles on observational cosmology convey his excitement at the prospects for new observations across the electromagnetic spectrum to constrain and guide theorists.

In 1970 Sciama moved to Oxford as a Senior Research Fellow at All Souls. He built a theoretical astrophysics group at Oxford and continued to support and train an impressive crop of students, including John Barrow, James Binney, Philip Candelas, and David Deutsch. In 1974 Oxford hosted a conference on quantum gravity, where Hawking announced his discovery that black holes emit black body radiation with a temperature proportional to their surface gravity. This discovery generated a great deal of interest, since it completed the analogy between “black hole mechanics” and the laws of thermodynamics. Sciama and his students contributed to the study of the thermodynamics of black holes following on the heels of Hawking’s work. In particular, Sciama and Candelas argued that the dissipation of energy by a radiating black hole could be understood physically based on the fluctuation-dissipation theorem from statistical mechanics. This work was closely tied to Sciama’s study of the vacuum in quantum field theory.

Sciama retained ties to Oxford for the rest of his life, but he also held a number of visiting positions. The most important of these were a part-time position at the University of Texas, Austin, from 1978-82, and his appointment as the director of the astrophysics group at the International School for Advanced Study (SISSA), Trieste in 1983. From 1982 until the end of his life, Sciama’s research efforts were mainly devoted to the decaying neutrino hypothesis. Sciama proposed that much of the elusive dark matter detected indirectly by astronomers consists of neutrinos left over from the early universe. If the three neutrino species have different masses, then more massive neutrinos decay into less massive neutrinos and emit light at a characteristic frequency. According to Sciama’s theory, the photons emitted by this process serve to ionize the interstellar medium within our galaxy and also explain a number of other puzzling phenomena. Particle physics and astronomical observations both placed tight constraints on the idea, and in 1998 satellite observations failed to detect an emission line predicted by the hypothesis.

Among numerous honors, Sciama was elected a foreign member of the American Academy of Arts and Sciences in 1982, and a fellow of the Royal Society in 1983. In 1959 he married Lidia Dina, a social anthropologist, and they had two daughters, Susan (b. 1962) and Sonia (b. 1964).