DENNIS WILLIAM SCIAMA

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The quarter-century period starting in the mid-1950s is sometimes referred to as ‘the renaissance of general relativity and cosmology’. Many contributed to this activity, but in the UK a major factor was the guidance and leadership provided by the warmly enthusiastic personality of Dennis Sciama, whose broad knowledge and deep insights greatly inspired many in their individual achievements.

EARLY YEARS

Dennis William Sciama, of Jewish descent, was born in Manchester, UK, in 1926. His father, Abraham Sciama, a very successful businessman in the textile trade, was also born in Manchester; Abraham’s grandfather came from Aleppo in northern Syria. Dennis’s mother, Nellie Ades, was born in Cairo, Egypt. Dennis had an elder brother, Maurice, who died in the 1970s. The Jewish community at Aleppo had been known as the ‘Aram-Tsova’, who identified Aleppo as the capital of a north Aramean kingdom subdued by King David in about 1000 BC (Ne’eman 2002). Dennis’s family name was previously ‘Shama’, but the spelling ‘Sciama’ was adopted to conform better to the Latin alphabet, perhaps indicating a phase in family history with Italian influence. In addition to ‘Dennis’ and ‘William’, he had also been given the name ‘Siahou’, but although he sometimes used the extra initial ‘S’ in his early life (see, for example, Temperley 1956; London Mathematical Society 1965), he never used it later.

Although having a distinct loyalty to his Jewish origins and friends, Dennis himself was an avowed atheist, as was his father, and neither generally followed Jewish religious practice. We quote from Dennis’s response in an interview with Spencer Weart, on 14 April 1978:
We’re Jewish, but we were never Jewish in the religious, orthodox sense; if I ever believed in God I stopped believing in it very young. I can remember my father telling me he didn’t believe in God, how we didn’t observe the Jewish orthodox practices. So in any practical sense there was no religious term to what I did or was interested in.

In later life, his position on religion seems to have softened somewhat, as in his 1998 book *Questo bizzarro Universo* (30)*, written in Italian (provided and translated by his daughter Sonia Sciami Daniels):

… the aim of physics is to account for all we observe in physical terms. The striking success of this physics programme so far has shown that one can go a long way in understanding nature without invoking supra-physical agencies. Of course, in the end one may find that this programme has its limits, but the aim of physics remains to push these limits further out. … we do not know whether there is a Creator who is capable of interfering with the universe. Of course there may be, but I take it that the aim of physics is to attempt to account for all we observe without appealing to outside interference. I want to make clear that I’m only against God as an explanation, in a limited sense. It may be in the end that God exists and takes the decision of fine tuning, because in the end you’ve got to be open minded about reality. But, by definition, Physics is the activity of trying to explain things without appealing to God.

Moreover, to a certain degree, he and his family did follow some Jewish practices, as Dennis had a Bar Mitzvah and a Jewish wedding, his two daughters also having Bat Mitzvah ceremonies.

His secondary schooling was at Malvern College, where he was a boarder between the ages of 13 and 18 years. There he received a high-quality education, particularly in mathematics and physics, which served him well for the career that he later devoted himself to. In fact, he originally viewed himself as becoming a mathematician rather than a physicist, and in 1944 he entered Trinity College, Cambridge, winning a minor scholarship in mathematics. However, he did not do well in Prelim to Part II Mathematics, and because this was during World War II he was required to study physics to obtain deferment from joining the forces, so he switched to the Natural Sciences Tripos, doing physics in the finals. As it turned out, this was fortuitous, because it became clear that Dennis’s abilities lay more with his instinctive understanding of physical principles rather than with formal mathematics. As an undergraduate he took an interest in other matters also, such as philosophy. In his first year he attended lectures given by Ludwig Wittgenstein in his rooms in Trinity. In his third year he attended a course of lectures on quantum mechanics given by Paul Dirac FRS, which impressed him immensely. After his period as an undergraduate at Trinity, he was conscripted into the army for two years, in 1947, because his BA degree result (a lower second) was not good enough for him to follow on directly to do research at Trinity. After his first six months in the army he moved to the Telecommunications Research Establishment (TRE Malvern) at Malvern College, Worcestershire, where he worked on the quantum mechanics of photoconductive materials, which was considered valuable for the detection of enemy aeroplanes—and it may be noted that several pioneers of radio astronomy (Bernard (later Sir Bernard) Lovell (FRS 1959), Martin (later Sir Martin) Ryle (FRS 1952), Tony Hewish (FRS 1968) and Francis (now Sir Francis) Graham-Smith (FRS 1970)) had also worked there previously.

* Numbers in this form refer to the bibliography at the end of the text.
On the strength of the internal reports he wrote during this time, on the quantum mechanics and group theory of these materials, he was accepted as a research student back at Trinity in 1949, working on cooperative phenomena under the supervision of H. N. V. Temperley. But during this time he started to develop other interests and began his largely self-taught study of relativity theory, gaining much of his early knowledge of the subject from the writings of Sir Arthur Eddington FRS, and also from the elegant little book *Space-time structure* by Erwin Schrödinger ForMemRS (Schrödinger 1950), which influenced his own later ideas on extending the framework of general relativity theory (hereafter GRT). His work on cooperative phenomena at Trinity lasted only for about 18 months, as his main interests gradually moved over to relativity theory and cosmology. His supervision was taken over by Paul Dirac, to cover these more fundamental interests—so Dennis gained the distinction of being one of Dirac’s very few research students! He attended the course on cosmology given by Hermann (later Sir Hermann) Bondi (FRS 1959), becoming friendly with both Bondi and Thomas Gold (FRS 1964), during this period, and later with Fred (later Sir Fred) Hoyle (FRS 1957). These three were the original architects of the steady-state model of cosmology (hereafter SST), according to which the overall state of the Universe remained the same for all time, despite its continual expansion, owing to the continual creation of new material, taken to be in the form of hydrogen appearing in a very uniform and extremely low-density form throughout the Universe, a theory to which Dennis became very attached. Somewhat connected with this was Dennis’s particular concern with Mach’s principle—the hypothesis that the inertia and inertial frames of local bodies are determined by the distant material of the Universe—whose importance was impressed on him by Bondi and Gold. These interests formed his main early concern in the years that followed.

While an undergraduate at Trinity, he was supported financially by his father, because his relatively poor examination result had precluded his obtaining a grant (although he did obtain a very small contribution of £20 from the Scott Fund). Science had not been in Dennis’s family background. Indeed, his father, although clearly a man of considerable intelligence and skills (such as at the game of bridge) and a very powerful personality, had no feeling for science or academia as such. He very much hoped that Dennis would move over into his own cotton cloth business, and there was much friction between the two over this issue. His father insisted that Dennis had no talent for science, because Dennis had actually done poorly in his final examinations, and should certainly join him in his business. At this point Dennis nearly succumbed, but he made the deal with his father that if he failed to obtain a Research Fellowship at Trinity College, Cambridge, for which he was applying, in 1952, then he would indeed join his father’s business. To his great relief and delight, however, he did obtain a Trinity Fellowship—an honour whose distinction his father appreciated, and he became somewhat reconciled to his son’s chosen profession as a scientist. However, some insight into Abraham Sciama’s utilitarian attitude to science can perhaps be gleaned from his response, when Dennis told him that he liked physics but was not so good at the mathematics, ‘can’t you pay for someone to do the mathematics for you?’ [reported by John D. Barrow FRS]. It should be remarked that despite Dennis’s downgrading of his own mathematical abilities, he had an extremely keen and quick logical mind, and was very well able to appreciate subtleties in mathematical arguments.

Dennis’s time under Dirac’s supervision could hardly have been less closely guided by Dirac, but it had its curious moments, as is revealed by a very short and a rather long story that Dennis liked to tell about this relationship. The short one he recounted as Dirac’s simple response ‘No’ when Dennis had excitedly asked him, ‘Professor Dirac, I’ve just thought of a
way of relating the formation of stars to cosmological questions; shall I tell you about it?’ In the longer story, it was Dirac who asked Dennis ‘Shall I tell you what I am doing?’ to which Dennis, very flattered and rather nervous, said, ‘Yes.’ Then, referring to a theory of classical electrons that he had been working on, Dirac started a long discourse: ‘I’ve generalized the theory to include this vorticity effect, and this is how I’ve done it ….’ At the end, Dennis, racking his brain for something safe to say, commented, ‘is this the most general way of doing it?’ to which Dirac responded, ‘I don’t know.’ A few weeks later, Dirac gave a seminar on the topic to a packed audience, and towards the end of his talk he said ‘Therefore I generalize my theory in the following way’, suddenly saying ‘at this point Mr Sciama made a most important remark to me: that this is not the most general way of doing it, and therefore I have done the following …’. In his embarrassment, Dennis felt that the floor could have opened up and he could have sunk into it.

Dennis was certainly not shy about communicating with the great, however: he wrote a letter to Albert Einstein dated (in the Einstein Archives) 22 December 1950, explaining his first attempt to do something in gravitational theory, related to Mach’s principle. Dennis was delighted when he actually got a detailed reply from Einstein, dated 28 December 1950; Dennis replied on 11 January 1951. Much later, Dennis was amazed to see in Einstein’s posthumous files a complete longhand version of Einstein’s letter that was subsequently typed.

A PERSONAL RECOLLECTION OF DENNIS’S TRINITY FELLOWSHIP YEARS

[WRITTEN BY R.P.]

Dennis was still a graduate student when he obtained his Trinity Junior Research Fellowship in 1952, and during this period he was able to explore his ideas freely, mainly those concerning Mach’s principle and SST, and he also considered possibilities for extending GRT to some kind of unified field theory. He obtained his Cambridge PhD in 1953 with a thesis entitled ‘Mach’s principle and origin of inertia’. During this Fellowship period, he wrote an elegant little book for the general public, The unity of the Universe (6) (published in 1959), in which he explained in simple direct terms the basics of cosmological understanding at that time, introducing the reader to SST and to his basic viewpoint concerning Mach’s principle. This provided a brief account of his specific ideas on how Mach’s principle could be formulated in terms of a direct interaction between distant masses, and he formulated this idea in more detail in his paper on the vector theory of inertia (1). The influence of his book is documented in Finding the Big Bang (Peebles et al. 2009 (hereafter FBB)), showing how, inter alia, it influenced Bob Dicke in developing his variable $G$ theory (see p. 38 of FBB), opened the mind of Bob Wagoner (see p. 258 of FBB), and was influential on Martin Rees (FRS 1979, PRS 2005–) before he came to Cambridge (see p. 262 of FBB).

At the same time as Dennis began his Trinity Fellowship, also in 1952, I entered St John’s College, Cambridge, as a PhD student in pure mathematics (algebraic geometry), initially under the supervision of William (later Sir William) Hodge FRS. A year previously, when I had been an undergraduate in mathematics at University College London, I had met Dennis when visiting my elder brother Oliver (FRS 1987), who was then a PhD physics student in Cambridge, and we had gone to the Kingswood Restaurant for lunch (a usual haunt for Oliver’s colleagues—including Dennis, who shared an office with Oliver). He spotted Dennis sitting at another table and introduced me to him, explaining that Dennis was an expert in cosmology.
This was of particular interest for me because at around that time I had been hearing Fred Hoyle’s remarkable series of radio talks (‘The nature of the universe. A series of broadcast lectures’, in 1951), in which he introduced the ideas of SST to the general public. Something that Hoyle had said had puzzled me about it and I was glad to have the opportunity to consult an expert on the subject for clarification. Apparently, on the strength of that encounter, Dennis felt that I was someone who was worth enticing from pure mathematics into the exciting areas of fundamental physics and cosmology, so that when I actually came up to Cambridge, Dennis made a special point of taking me under his wing.

The only serious physics that I knew at the time consisted of those parts of applied mathematics that I had picked up from my undergraduate mathematics degree course in London, and a bit of GRT (Schrödinger’s *Space-time structure* again) and some parts of relativity and quantum theory that I had learnt from Oliver. From Cambridge lectures I picked up some more, mainly from the superb lecture courses of Dirac and Bondi, and from the important understandings of general relativity (GR) that were provided by Felix Pirani (who had been a student of Alfred Schild’s in Toronto). But Dennis taught me much more about current activity, which he had a remarkable ability to keep up with and to explain in simple terms, not only in relativity and cosmology but also in other important areas such as particle physics and quantum (field) theory, and in the logical relationships and overall connections between these various topics. His sense of excitement was always in evidence, and it was very infectious.

It would seem that all this time he was hoping to persuade me to change my official subject of research from pure mathematics to physics, but to me this would have been too abrupt an action to take, particularly as there were many aspects of mathematics that interested me greatly and which, as things turned out, were to have important roles in my later research into physical foundations. Nonetheless, I did spend much mental energy on issues of physics, particularly when in Dennis’s company. I used to accompany him on trips from Cambridge to Stratford-upon-Avon, to attend Shakespeare plays, where these trips would be undertaken by Dennis driving me at a not inconsiderable speed (in his Jaguar) around corners, at which point he would comment on the remarkable accelerating effect that the ‘fixed stars’ have on the passengers, in accordance with Mach’s principle.

In current times it is not uncommon for physicists and philosophers to be somewhat scornful of Mach’s principle—and, indeed (for different reasons), of some of Dennis’s other primary concerns during his early period, namely SST and unified field theories—arguing that Mach’s principle is perhaps either meaningless or an immediate consequence of other normal assumptions. It is now generally accepted that although Mach’s principle had an important role in Einstein’s early thinking, in the years preceding his finalizing of his GRT, it is not fully incorporated into the theory that Einstein finally came up with. This seems to have been Dennis’s view also, because he spent many years looking for alternative formulations of the foundations of physical theory, in which Mach’s principle indeed formed a key ingredient. His initial formulation (1) was a vector theory, modelled on electromagnetism, in which the velocities of the sources of the field contribute to their effects on other particles, which was the scheme he described in popular terms in *The unity of the Universe* (6). Eventually he came to realize that these attempts could at best be approximations to some fully nonlinear scheme and that it would be hard to avoid the conclusion that this scheme had to be essentially Einstein’s GRT. Dennis then formulated a way in which Mach’s principle could still have a role as determining appropriate boundary conditions for that theory, and he combined forces to publish a paper on this (17) with his student Peter Waylen and with Robert Gilman, who was a student under
John Wheeler (ForMemRS 1995) in Princeton and had independently come upon a similar prescription, apparently stimulated by some of Dennis’s earlier writings. Later, Derek Raine, a student of Dennis’s (who graduated in 1971), formulated a more complete criterion for the satisfaction of Mach’s principle in solutions of the equations of GRT (Raine 1975, 1981). In more recent years, others have taken up the challenge of finding a purely ‘Machian’ formulation of GRT, using different ideas to obtain a purely ‘relationist’ formulation of GRT (see, for example, Barbour 2002; Barbour et al. 2002). Yet it is probably fair to say that most physicists do not now rate the issue of Mach’s principle particularly highly. A good summary of Mach’s principle, and Dennis’s contribution to it, is given by Paul Tod in Ellis et al. (1993).

In my own case, however, I certainly did gain something very valuable from Dennis’s view of Mach’s principle (and from his speedy driving), because during trips to and from Stratford we would often contemplate the hypothetical situation of the gradual removal of all the matter in the Universe external to the contents of the car. Mach’s principle would seem to have the implication that as each distant star was removed, the inertia of the material within the car would be very slightly reduced. Once all the external material had been eliminated, there would be no experience of inertial forces and no meaning to whether the car was in motion or not. The dynamics of all motions would have to be taken in relation to the body of the car, because there would be no external objects with respect to which locations, velocities or accelerations could be measured; the dynamics of everything within the car would be independent of the car’s motion (if that motion could be considered to have any meaning). All motions would be taken only in relation to the body of the car. But the argument would not stop there, because we could imagine that the constituents of the car itself could be removed until there were only a few particles left. It was clear to us that (as Einstein had believed) leaving ourselves just with Minkowski space (the flat space-time of special relativity), when all the material was removed, would not be a solution in accordance with Mach’s principle, because Minkowski space does determine inertial frames, distinguishing rotating from non-rotating motions. Thus, when there are but a few particles left, their rotations would have meaning only when taken relative to each other’s rotations. With individual particles, we would have to consider the quantum-mechanical aspects of the rotational relations between them, and this would have to determine the kind of geometry that could arise; that geometry would thus have to be some kind of quantum geometry!

Charged particles would seem to give a nonsensical answer, because with inertia reduced to zero and with finite electric forces, accelerations would become infinite unless the electric force were also reduced to zero. It made more sense simply to consider quantum-mechanical spins, spin being the aspect of rotation that individual quantum particles possess—the very meaning of rotation being what Mach’s principle is largely about. So I thought of the quantum rules governing encounters between a few spinning particles, these spins always being determined solely by their relations to one another, and I eventually came up with the theory of spin-networks (Penrose 1971), a (Machian) scheme that in recent years (in a somewhat modified form) has become one of the key ingredients of the loop-variable approach to quantum gravity (Ashtekar & Lewandowski 2004), one of the leading current candidates for solving the deep problems of bringing together Einstein’s gravitational theory with quantum mechanics. So, in this case at least, Dennis’s deep considerations of the implications of Mach’s principle seem to have borne some genuine fruit, in terms of which there is much current activity in foundational physics.

Dennis was also concerned with another consequence of Mach’s principle, whereby the total amount of matter in the Universe ought to be what determines the magnitude of a body’s
inertia, and this would manifest itself in terms of the observed value of the gravitational constant. Accordingly, Dennis set much store by the roughly observed relation
\[ G \rho \tau^2 \approx 1, \]
which relates Newton’s gravitational constant \( G \) to the average density of the Universe \( \rho \) and the inverse Hubble constant \( \tau \). We may take this as an expression of the fact that, according to standard GRT cosmology, the spatial curvature is close to zero, where the ‘\( \rho \)’ in this relation then encompasses not only the density of ordinary matter but also a contribution whose significance has become clear only in comparatively recent years, namely that due to the highly abundant dark matter. Thus, this ‘Machian’ relation is remarkably closely satisfied in the part of the Universe dominated by dark matter. However, it is not consistent with the effective energy density provided by the cosmological constant (or ‘dark energy’) that observations have shown dominates the Universe at recent times.

SST appealed to me emotionally, and Dennis’s defence of it carried a lot of weight with me. As will be described in the next section, Dennis eventually abandoned this theory, reluctantly but with great courage and honesty, when the evidence against it from distant quasars and from the thermal nature of the microwave background became too strong. Even before this evidence I had had reservations similar to those sometimes expressed by Bondi, that the philosophical virtues of the SST would seem to be seriously offset if it could be shown that it was in contradiction with an even more beautiful idea, namely Einstein’s GRT. So, at some stage (I cannot recall exactly when), I tried to see whether a rigorous mathematical theorem could be proved showing that even in the presence of irregularities there is an inconsistency between SST and standard GR (taken together with some condition of energy positivity on the matter density). Using properties of light-ray focusing, I was able to establish for myself (although I never published this result) the existence of such a theorem. This mode of thinking later bore fruit in the first singularity theorem that I was able to prove (Penrose 1965; Hawking & Penrose 1970), leading to the conclusion that irreversible gravitational collapse would lead to singularities, irrespective of local irregularities (assuming that suitable energy-positivity and causality assumptions are made). It may perhaps be mentioned that the philosophical standpoint of SST has echoes in a proposal I have recently suggested, referred to as conformal cyclic cosmology (Penrose 2008).

A much earlier input into this singularity theorem illustrates another particular strength of Dennis’s leadership. He was exceptionally good at bringing people together who might have things of direct importance to convey to each other (figure 1). On one occasion during the academic year 1957/58 he told me of a lecture that David Finkelstein (then at Stevens Institute of Technology, New Jersey) was giving at King’s College in London and he very strongly encouraged me to go to London to hear it. In this talk, Finkelstein described his own approach to extending the Schwarzschild metric across the surface we now refer to as a black hole’s horizon, although in those days it was commonly thought of as a ‘singularity’. He elegantly demonstrated a rapid way of obtaining almost the entire space that we now commonly refer to as the Kruskal extension (Finkelstein 1958; Kruskal 1960). I was most impressed, but seeing that there was still a singularity at \( r = 0 \) I was left wondering whether there might be some general principle according to which singularities might be inevitable under such circumstances. On returning to Oxford I tried to glean something of what such a principle might be, but at that time I was totally without any of the machinery that would later prove what was required. All that I then had at my disposal was a facility with 2-spinors (the crucial expertise for which
I had gained from Dirac’s lectures, and a direct consequence was a beginning of applications of 2-spinor techniques to GRT that I later developed (Penrose 1960). Afterwards, Finkelstein would comment that our meeting on this occasion resulted in our exchanging roles, for I had previously been working on the discrete theory of spin-networks, which I explained to him, and he on continuous physics (such as GRT). After this encounter, his own interests switched to discrete-space-time physics, whereas I worked mainly on the continuous GRT (and, later, twistor theory).

Dennis’s instinctive skill in bringing people together who might usefully influence one another is aptly illustrated in the following quote from Kip Thorne, who regards Sciama as a mentor of students comparable with the influence of John Wheeler in the USA and Yakov Zel’dovich ForMemRS in the USSR (Thorne 1994, p. 272):

Sciama was a catalyst: he kept his students closely in touch with the most important new developments in physics, worldwide. Whenever an interesting discovery was published, he would assign a student to read on it and report to the others. Whenever an interesting lecture was scheduled in London, he would take or send his entourage of students down on the train to hear it. He had exquisitely good sense about what ideas were interesting, what issues were worth pursuing, what one should read in order to get started on any research project, and whom one should go to for technical advice … by having his students solve the most challenging problems, he could move more quickly from issue to issue than if he paused to try to solve them himself.
In my own experience, we also see an instance of Dennis’s generosity in scientific matters, for in the months after my encounter with Finkelstein I had developed this 2-spinor formalism to a point that Dennis believed it would be appropriate to present it to the Xth International Conference on General Relativity and Gravitation in Royaumont, near Paris, 21–27 June 1959. The programme was full by that time, so Dennis offered me half of the time that had been assigned to his own talk (8), and I presented my ideas then (Penrose 1962).

Dennis’s interests in generalizations of GR also contributed to our conversations, to a considerable degree. Many of these schemes struck me as somewhat contrived and not very elegant. The one exception was his idea that materials with intrinsic spin should be described by a torsion in the connection. Initially Dennis was not aware that Tom Kibble (FRS 1980) had also put essentially the same idea forward, and that Élie Cartan (ForMemRS 1947), much earlier, had also played with introducing this kind of proposal into GR. Andrzej Trautman later revived the idea, referring to it as the ‘Einstein–Cartan theory’. It is now often referred to as the ‘Einstein–Cartan–Sciama–Kibble’ (or ECSK) theory. It is a fine idea, but I have never been able to come to a conclusion about its physical status. In relation to Dennis’s approaches to generalizing GRT, it should, however, be remarked that Yuval Ne’eman states, ‘Dennis Sciama was a pioneer in applying the Yang–Mills approach to gravity’ (Ne’eman 2002).

Some of Dennis’s ideas for broadening GR to a unified field theory (5, 7, 8) involved using complex coordinates. Perhaps that had some influence on my moves into twistor theory (Penrose 1967). I don’t think that Dennis was very keen on my doing twistor theory, but at least he tolerated it—and he didn’t actively try to get me to give it up, as did Wheeler and Zel’dovich, independently at one conference we all attended! My debt to Dennis is enormous, and I expressed my appreciation by dedicating my book The road to reality (Penrose 2004) to his memory.

An aside remark by G.F.R.E.: it has sometimes been said that one of the most important contributions that Dennis made to GRT was by interesting Roger Penrose in the subject, as evidenced in this part of the memoir. This is because of the major contributions that Penrose has made to the subject, which were of a transformational nature (for example, Penrose diagrams are now part of the working tools of every relativist). I concur with that judgement.

THE DEMISE OF THE STEADY-STATE COSMOLOGY

In the late 1950s, SST was in the ascendance, at least in Britain. But there were many issues to be faced, in particular how the elements could originate and how transient structures such as galaxies and stars could form in such a Universe. Dennis entered this debate with enthusiasm, and showed his great strengths of looking at the physical and astrophysical aspects of the problem as an integrated whole, emphasizing that it had to be tested by observations wherever possible. First he made a significant contribution by proposing a detailed model of galaxy formation in the SST Universe, presented at an International Astronomical Union symposium in 1953 and published in 1955 (3, 4). Next, together with Bondi and Gold in 1954, he published a paper showing that the data were insufficient to substantiate the Stebbins–Whitford effect of an excess reddening of spectra of elliptical galaxies, which was claimed by some to disprove SST (2) (for a detailed account see Kragh (1996)).

The optical data were indeterminate, and the debate moved on to radio sources. A considerable discussion ensued as to whether these were extragalactic or not. In 1963 Dennis
challenged Martin Ryle’s conclusion that radio source counts disproved the SST cosmology, by using a model supporting the idea they were local sources rather than at cosmological distances (9). The cosmic microwave background (CMB) was discovered in late 1964 to early 1965, and was proposed to be a relic of radiation from the Hot Big Bang (see FBB for a full narrative). In 1966 Dennis searched for alternatives (10) but declared that a demonstration that the microwave background consists of blackbody radiation would almost certainly enable SST to be ruled out. However, he was not prepared to abandon it at that stage, because the blackbody character had not been sufficiently well established at that time—that needed observations at other wavelengths. In early 1966 he tried to extend local models of the discrete radio sources to quasars, proposing a local model for them also. But in the August he and his student Martin Rees published a paper on the inverse Compton effect in quasars (11), showing that quasars could be at cosmological distances, contrary to claims by Hoyle, Burbidge and Sargent, who had claimed that inverse Compton losses might rule out quasars at great distances. He then plotted the redshift of quasars, and at first this seemed to favour SST. However, Rees showed that it actually came out the other way, and their paper in Nature in September 1966 (12) was the first to point out that this distribution was evidence against SST.

According to Dennis (see Weart 1978):

one had to take a view as to where the quasars were, because if you thought the quasars were local, you could also get out of the radio source count. You could say the radio source count (slope) being steep might be due to quasars, and if the quasars were local then the steepness was not cosmological.

The abstract for this paper states, ‘The purpose of this report is to point out that recent measurements of the red-shifts of quasars provide the most decisive tests of the steady state theory.’ On this basis, together with increasing evidence for the blackbody spectrum of the cosmic background radiation, Dennis recanted and became a strong supporter of the Hot Big Bang model of the early Universe. Indeed, Dennis was never prepared to accept non-cosmological redshifts for quasars, so he abandoned his idea of a galactic population with a ‘local hole’ as soon as the redshifts came in. He wrote to Bob Dicke (FBB, p. 197):

As you may have heard I have recanted from the steady state theory, and have taken such a liberal dose of sackcloth and ashes that I am now more orthodox than the orthodox (although I don’t suppose this phase will last long). Anyway you can tell Peebles that I now nearly believe that the excess background has a black body spectrum. I hope to see him and you in New York so that I can capitulate in person.

This recantation made a great impression on those who knew how strongly he had previously supported SST. It is a model of how science ought to proceed.

MEETING WITH EINSTEIN

In 1954 Dennis took a two-year leave of absence from his Trinity Fellowship to take up visiting fellowships in the USA, where he spent the academic year 1954/55 at the Institute for Advanced Study in Princeton and the year 1955/56 on an Agassiz Fellowship in Harvard, postponing the third and fourth years of his Trinity Fellowship until his return from the USA in 1956. In Princeton he came into contact with many very well known scientists such as
Robert Oppenheimer (ForMemRS 1962) and Albert Einstein ForMemRS. His experiences with these two were very different, as the following communication from John Barrow clearly illustrates:

My memory of the rest of the story was that he had been a young visitor to The Institute for Advanced Study, hoping to think about the quantum mechanics of continuous creation in the steady state theory. He stressed that young post docs knew very little in those days. He had to give a seminar after he arrived and talked about the steady state. Oppenheimer was in charge of the seminar. Lots of other famous people were in the front row. … At the end of the talk Oppenheimer (as usual) sums up the talk and asks a first question. On this occasion Dennis said that he just said something like. ‘Your opening historical remarks I found very interesting but as for what followed, I thought it was complete nonsense.’ (Oppenheimer was often nasty like this it seems.) Dennis said this was rather difficult to respond to!

Dennis’s lecture was a ‘Theoretical Physics Seminar’ entitled: ‘Steady-state theory of the expanding Universe’, given on Tuesday, 26 October 1954. Barrow recounts that on a later occasion

Dennis went to see Einstein to talk about Mach’s Principle, having a prepared introduction that he was ‘coming to defend your former self against your present self’. Einstein apparently laughed so uproariously at this that it was difficult to get the conversation back on track. He failed to persuade Einstein … .

This meeting with Einstein occurred in April 1955, just one week before he died, and Dennis referred to it as a wonderful experience, with Einstein describing some of his own work, his doubts about quantum theory, and so on.

After Dennis’s period at Princeton, he spent the following academic year, 1955/56, at Harvard as an Agassiz Fellow. He then returned to Cambridge to complete the final two years, 1956–58, of his Trinity Fellowship. Despite his superb teaching skills, Dennis was reluctant to take on a proper academic teaching job, preferring to concentrate on research. He was therefore happy to have the opportunity to spend the next two academic years, 1958–60, as a research associate at King’s College, London, under the lively leadership of Bondi, and also Pirani, financed by a US Air Force grant. (At that time the US Air Force was happy to finance pure research into gravitational theory.) During this period his travels took him to Israel, where he met Lidia Dina, a Jewish girl from Venice, who at that time had been studying English at the Hebrew University in Jerusalem for a couple of years. He and Lidia were married not long after this, in 1959. Dennis then returned to the USA, with Lidia, for the year 1960/61, to work with Gold at Cornell (under finance from the US Department of Defense), and she obtained a Master’s degree while there.

**RETURN TO CAMBRIDGE 1961: SCIAMA AS A RESEARCH SUPERVISOR**  
**[WRITTEN BY G.F.R.E.]**

In 1959 the Department of Applied Mathematics and Theoretical Physics (DAMTP) was set up in Cambridge by George Batchelor FRS. This provided a departmental structure within which Dennis’s interests could find a home, so he decided to apply for a lectureship in mathematics, which he obtained in 1961. Two years later, in 1963, he was elected to a Fellowship at Peterhouse. This particularly pleased him because of their excellent culinary reputation. He held this Fellowship until he moved to Oxford in 1970.
DAMTP was initially housed in the Phoenix wing at the top of the Cavendish Laboratory in Free School Lane, where, *inter alia*, Dirac and Hoyle lectured, and Dennis gave lectures on GRT based on Schrödinger’s book *Space-time structure* (Schrödinger (1950); mentioned above by R.P.). In 1964 the department moved to the old Cambridge University Press premises in Silver Street, where Dennis was instrumental in the implementation of almost compulsory daily coffee times as a venue for scientific discussions to take place, low tables with white tops being provided so that they could be written on with erasable ink to illustrate ideas being developed. Typically Dennis would lecture on Saturday mornings, taking coffee in the tea room. There he would be surrounded by his students and associates, handing out and commenting on the latest batch of preprints that he had been sent by his extensive network of contacts worldwide. Seminars were constructive rather than hostile, and open discussion of ideas was encouraged, with a strong emphasis on observational testing of any ideas proposed. Martin Rees writes (in *FBB*):

The mid-1960s were years of ferment in observational and theoretical cosmology. The discovery of the CBR was of course the pre-eminent event, but these years also saw the emergence of ‘relativistic astrophysics’: the first high-redshift quasars, the discovery of neutron stars, and the first results from space astronomy (especially X-ray astronomy). Dennis Sciama was ‘plugged in’ to all these developments. He encouraged his students to interact, and to learn from each other. He eagerly shared new preprints (and correspondence, news of conferences, and so forth) with his students and post-docs, and with colleagues such as Roger Tayler. For instance, I learned during the coffee-time sessions about Hoyle and Tayler’s work on helium formation, also about the debate with Moscow relativists about the nature of singularities.

Dennis set great store by selecting very good students and then strongly supporting them in whatever they wanted to do. Gary Gibbons FRS comments (personal communication):

I have always been extremely grateful for the faith that Dennis had in me and the effort he took to obtain the means for me to enter the world of research. Without it, it is almost certain I would have had to get a job outside academe.

His supervision style was in the main to simply tell one that this was an interesting idea to work on, now go away and find out about it, and by the way Schücking or Bondi or Pirani or Penrose or Ehlers is the person to talk to about it, why don’t you go and see them. In this way he encouraged his students to work across a wide range of problems that he thought about deeply but did not himself work on. I was his first PhD student, with his encouragement working on anisotropic (Bianchi) cosmologies and singularities in cosmology, and greatly benefited from this style of supervision. It was of course different if he himself was engaged in calculations on the topic concerned: then the interaction would be intense, and on a daily basis.

This period in Cambridge allowed Dennis to build up a very powerful research group, with many visitors including John Wheeler and Charles Misner, and an astonishing succession of research students. It is not possible to mention them all in the space available, but the point to be made is the remarkable quality and later successes of these students. Here I focus on just three who became Fellows of the Royal Society; the others are listed in the Sciama ‘Family Tree’ contained in the Sciama Festschrift volume (Ellis *et al*. 1993), together with a list of the formidable array of books they have produced.

Stephen Hawking (FRS 1974) started work on SST, challenging Fred Hoyle’s proposal of an action-at-a-distance gravitational theory in that context, and then did some very solid work on anisotropic Universe models and perturbation theory for standard cosmological models.
He then made his mark by applying to the cosmological case the innovative techniques that R.P. had developed for proving occurrence of space-time singularities at the end point of gravitational collapse. He was thus able to settle a debate that had been going on for decades: classical GRT, with some plausible energy assumptions, predicts that there was an initial singularity, a start to space-time, at the beginning of the Universe. He went on to work on uniqueness theorems for black-hole collapse, and with others developed the Four Laws of Black Hole thermodynamics. This led on to arguably his greatest discovery, that quantum field theory effects result in black holes’ emitting blackbody radiation (‘Hawking radiation’). This led on to his initiation of the ongoing discussion about the black-hole information paradox, a major stimulus for thought in the relation between quantum theory and gravity. Additionally he did innovative work on the wavefunction of the Universe and was co-organizer and participant in the Nuffield workshop that showed how the inflationary Universe theory could provide a solid theory of structure formation in the expanding Universe—a key result in present-day cosmology. He went on to achieve international fame through his popular books, particularly *A brief history of time*. His students number many noted scientists, and he currently has more than 66 papers with over 100 citations.

Brandon Carter (FRS 1981) did key work on the geometry of the Kerr solution (the space-time representing a rotating black hole), in particular examining their geodesics and determining their global structure in a seminal paper, and made major contributions to the important discussion on black hole uniqueness theorems and black-hole thermodynamics. Following on from work of Dicke and others, he went on to provide the first full formulation of the Anthropic Principle: the notion that many aspects of the physics of the Universe are fine-tuned so as to allow the existence of life. This very controversial paper has been highly influential, with the ensuing debate still raging today.

Martin Rees initially worked on quasar number counts with Dennis as mentioned above, as well as CBR anisotropies (as discussed below), and then went on to examine, *inter alia*, astrophysical aspects of quasars, extragalactic radio sources, black-hole models for active galactic nuclei, γ-ray bursts, and theories of galaxy formation, as well as anthropic coincidences. He was one of the first to propose that enormous black holes power quasars, which is a key aspect of high-energy astrophysics, and he was the first to write a paper (in 1968) on possible CBR polarization—now a subject of intense study. He has become one of the premier astrophysicists in the world (he currently has more than 91 papers with over 100 citations), some of his posts being Plumian Professor of Astronomy and Experimental Philosophy at Cambridge, Astronomer Royal, President of the Royal Society, and Master of Trinity College, Cambridge. His former students include Roger Blandford FRS and Jim Pringle FRS. He was awarded the Crafoord Prize 2005 for contributions towards understanding the large-scale structure of the Universe.

Other students of Sciama’s from this period who have been elected Fellows of the Royal Society are Gary Gibbons and myself. As for Dennis’s own work, his most important contribution, apart from the work on SST discussed above, was his early work on CMB anisotropies. Together with the crucial paper published by Arthur Wolfe and Ray Sachs at about the same time, this was pioneering work on what has become one of the most important aspects of cosmology today. He published two papers on the relation between the peculiar velocity of the Sun and the CMB dipole anisotropy in 1967, one jointly with John Stewart (13, 14), ‘These two papers stimulated experimentalists towards direct observation of the CMB dipole’, according to B. Melchiorri *et al.* (2002). His important paper with Martin Rees, ‘Large-scale
density inhomogeneities in the Universe’ (15), showed how photons falling into gravitational potential wells resulting from growing mass concentrations would leave their imprint on the CBR anisotropies. This Rees–Sciama effect is the subject of active research and observational test today.

He also worked on the interaction or matter and radiation in the expanding Universe, for example observational consequences of the interrelation between X-ray and radio emission by intergalactic matter, and how this delineated its possible thermal history. His influential papers ‘The recent renaissance of observational cosmology’ (18) and ‘Astrophysical cosmology’ (20) usefully summarized knowledge at the time—and of course emphasized his complete conversion to the Hot Big Bang expanding Universe picture, as did his lucid semi-popular book Modern cosmology (19), published in the same year. He was also pivotal in the discussions in the UK community that led to the development of experimental work on gravitational radiation (see (21, 22)). Gary Gibbons states (personal communication), ‘I believe that without Dennis, gravitational radiation studies would not have developed in the UK.’

OXFORD: RESEARCH IN QUANTUM GRAVITY, 1970–85

In 1970, All Souls College in Oxford advertised a senior Fellowship, for which mathematics was one of the allowed areas of study. By this time, Dennis had considered that his lecturing load at Cambridge had become very heavy and, as he was also supervising about 10 research students, he was finding this load excessive. Even before this, he had been always keen to reduce his university lecturing load, taking the view that such lecturing interfered with his time for research. Accordingly, he applied for the Fellowship, but without much hope of success because All Souls had very little scientific tradition, only one of the 65 Fellows at the time being a scientist (this was the distinguished theoretical physicist Richard Dalitz FRS). However, Dennis was appointed to the Fellowship, so he moved operations from Cambridge to Oxford. He set up a research group in a temporary building, which was a rather small but comfortable wooden hut, built with money from the Radcliffe Trust, on the lawn in front of the main Astrophysics Department building; this department was headed by Donald Blackwell. Dennis was able to join forces with Dirk ter Haar, a Reader in Theoretical Physics, and his students, who had research interests overlapping Dennis’s, in theoretical astrophysics. Dennis asked Subrahmanyan Chandrasekhar FRS (later a Nobel laureate) to visit for a sabbatical year in his first full year of operation in Oxford (1971–72). Chandra’s presence was very influential and helped in getting the group off to a flying start.

Dennis’s excellent reputation as a research supervisor enabled him again to build up a strong group of research students. One area that he thoroughly encouraged as an up-and-coming topic was the exploration of connections between particle physics and cosmology. The previously unexpected interplay between the large and the small intrigued him greatly, for example the relation between neutrino physics and helium formation in the early Universe. He was also early in realizing the importance of quantum gravity, in its relation to cosmology. Having abandoned the SST he fully realized that a proper understanding of cosmology could not come about without having some deeper understanding of the rules governing the Universe’s origins, which meant the Big Bang. Rather than simply accepting this initial space-time singularity as an unfathomable starting point, he took the view that the possession of a consistent quantum gravity theory could be the key to a further understanding of cosmology.
Thus, alongside the more conventional activities in theoretical and observational astrophysics, and cosmology, such as his examination with John Miller (24) of gravitational collapse to the black hole state, he moved into research in the highly theoretical and deeply speculative area of quantum gravity. Despite the acknowledged difficulty of this area, the bringing together of the foundational aspects of combining quantum (field) theory with those of GR was something that greatly appealed to Dennis.

In January 1974 Stephen Hawking announced his remarkable finding that, through quantum effects in a curved space-time background, a black hole must have a temperature in proportion to its surface gravity, thereby vindicating and making more precise Jacob Bekenstein’s earlier conclusion that a black hole must have an entropy in proportion to the surface area of its event horizon. Dennis quickly recognized the importance of this result, hailing it as initiating a new revolution in our understanding of how quantum theory and GR must fit together, and where the third subject of thermodynamics remarkably enters into the discussion in a central way. Together with Christopher Isham, of Imperial College, London, and R.P., he rapidly organized the first of three Oxford conferences on quantum gravity, which was held at the Rutherford Laboratory on 15 and 16 February 1974, this being the occasion on which Hawking first made a public presentation of his very striking new result. The second of these conferences, organized by the same three people, was held in 1979, whereas Dennis was less involved in the third, held in 1984. The proceedings of all three were published by Oxford University Press, those co-edited by Dennis being published in 1975 and 1981.

Dennis also worked directly himself on black-hole thermodynamics, introducing a new angle on the issues by means of the fluctuation dissipation theorem. This concerns thermodynamical deviations from equilibrium, a result that been developed after an initial realization about Brownian motion due to Einstein and Smoluchowski in around 1905. With Philip Candelas he wrote ‘Irreversible thermodynamics of black holes’ (23). Black holes are shown to obey the principles of irreversible thermodynamics in the form of a fluctuation-dissipation theorem for their zero-point quantum fluctuations. Moreover, Hawking radiation is shown to be related to the macroscopic radiation of a non-stationary black hole in accordance with Onsager’s principle.

The breadth of Dennis’s interests can to some extent be gauged from the variety of topics taken up by some of his most successful research students of this period, although the areas of work for which these former students later became well known were not necessarily the topics that they researched in while under Dennis’s supervision. For example, his student David Deutsch (FRS 2008), who had been working on the problems of quantum field theory in a curved space-time background (25), later became a pioneer of quantum computing and a strong proponent of the many-worlds interpretation of quantum mechanics. In addition, Tim Palmer (FRS 2003), who worked on the problem of gravitational energy-momentum in space-times without isometries, came up with a formalism based on the Synge world function (more generally, based on tensors on the tangent bundle to space-time) from which quasi-local expressions for gravitational energy momentum could be formulated. He later became an important figure in the Meteorological Office, concerned with new procedures for predicting the weather—partly inspired by Dennis’s ideas about the use of techniques in non-equilibrium thermodynamics, in particular on the principle of maximum entropy production.

By way of contrast, James Binney (FRS 2000), who worked on galactic dynamics while a student of Dennis’s, became a world leader in galactic dynamics, inter alia publishing a magisterial textbook on the subject. John Barrow worked in cosmology, particularly on the
early conditions in the Universe and its dynamics, and observational properties of anisotropic Universe models. He then developed very broad interests, in particular writing a very influential book on the Anthropic Principle with Frank Tipler and undertaking observational and theoretical studies of the possible variation of the ‘constants’ of nature over space and time. He has become a distinguished popularizer of science, with many excellent popular books to his credit, and is organizer of the Millennium Mathematics Project. Philip Candelas, who worked on quantum field theory, thermodynamics and horizons under Dennis, became a well-known string theorist, and succeeded R.P. as Rouse Ball Professor of Mathematics in Oxford. During this period, Dennis’s method of working with students was the same as at Cambridge. Tim Palmer recalls:

After my work diverged away from the problem which Dennis set me, I think Dennis was happy to give my work a rather light touch as a supervisor, and he let me follow my own nose. In fact I remember him saying to me once at an early stage in my D.Phil., that his preferred method of supervision—one, he said, that had worked well with past students such as Stephen Hawking and Brandon Carter—was to set a basic problem and then let the student sink or swim. This comment scared the life out of me at the time, and there were certainly moments when I wondered whether my decision to do GR at Oxford was the right one, but in the end it worked out well!

During this period, together with Bill (later Sir William) McCrea FRS and John (now Sir John) Polkinghorne FRS, Dennis initiated the Cambridge Monographs on Mathematical Physics, a prestigious series of accounts of major areas of theoretical physics. The first volume was *The large-scale structure of space-time* by Stephen Hawking and George Ellis, which was, in 1973, the first comprehensive text on global techniques in GR and was dedicated to Dennis. There are now 98 titles in the series. A present-day description states:

This highly acclaimed series of monographs provides introductory accounts of specialized topics in mathematical and theoretical physics for graduate students and research workers. The monographs in this series are of outstanding scholarship and written by those at the very forefront of research. Subject areas covered include cosmology, astrophysics, relativity theory, particle physics, quantum theory, nuclear physics, statistical mechanics, condensed matter physics, plasma physics, and the theory of chaos.

Initiating and guiding the series was a substantial contribution to these subjects.

While based at Oxford, Dennis spent the academic year 1977/78 as Luce Professor at Mount Holyoke College, Massachusetts, and was a part-time professor in the Physics Department at the University of Texas, Austin, from September 1978 to May 1983 for one semester each year. He was associated with John Wheeler’s group in Austin, as well as with the Relativity Center. He interacted with Bryce DeWitt, Cecile DeWitt, John Wheeler, Philip Candelas, Richard Matzner, Larry Shepley, David Brown, David Deutsch and Claudio Teitelboim. Alfred Schild (who had founded the Relativity Center) was dead by then; Steven Weinberg (ForMemRS 1981) had not yet arrived. It was here that he started his work on decaying dark matter with his student Adrian Mellot.

**INTERNATIONAL SCHOOL FOR ADVANCED STUDIES (SISSA), 1983–99**

In 1983 Dennis became Professor of Astrophysics and Head of the Astrophysics Sector at SISSA, Trieste, first in the old Bellavista building next to the railway line at Miramare, and then in the new one next to the International Centre for Theoretical Physics (ICTP) at Grignano, and also
ran cosmology for the ICTP. Initially Dennis shared the leadership of the SISSA Astrophysics Sector with Nicolo Dallaporta, and they worked very closely together while he was getting things set up. He ran a very democratic group with frequent sector meetings, being particularly supported by John Miller, Antonio Lanza, and (for a while) Marek Abramowicz and G.F.R.E. He took great care in selecting very good students (some Italian, some international) for the astrophysics sector, and supervising them on a very wide range of projects in gravitation theory, cosmology and astrophysics. The group used to have lunches in the ICTP canteen and weekly sector dinners in restaurants in town, or up on the Carso above Trieste. He used to go back to his and Lidia’s flat in Venice on many weekends. He also had a flat in downtown Trieste, and his landlady was also the cleaning lady for his office at SISSA—leading to interesting role reversals between the office and the flat! Students from this time included Stefano Liberati, Paolo Molaro, Paolo Salucci, Sylvia Mollerach and Antony Valentini.

His own work in this period was mainly on the massive-decaying-neutrino theory for dark matter, accounting in a unified way for a whole variety of observational phenomena. He suggested that most of the dark matter in the Milky Way consists of tau neutrinos whose decay into photons is mainly responsible for the widespread ionization of hydrogen in the interstellar medium (outside H II regions), and almost on a weekly basis he would excitedly announce some new possible matter–radiation interaction with possible observational effects (for example (27–29)). This was a typically sophisticated theory linking cosmology, astrophysics and high-energy physics, which he summarized in his last book; however, it became increasingly baroque and ultimately failed: it was contradicted by observations. But that of course is to Dennis’s credit: he always insisted on testing theories in all possible ways, and devised many tests of this particular theory; the connection between neutrino properties and astroparticle physics remains of fundamental interest (Raffelt 2002). His last paper on the topic was published posthumously (33). He also took part in an intriguing series of papers on sonoluminescence considered as a quantum field theory effect with Liberati, Matt Visser and others (31, 32), which has generated considerable interest. He additionally returned to the issue of the nature of the quantum vacuum, and with Derek Raine and Peter Grove he revisited an old problem in ‘Does a uniformly accelerated quantum oscillator radiate?’ (26). The introduction to their paper starts out, ‘The apparently straightforward question as to whether various uniformly accelerated systems radiate has turned out to be quite subtle.’ This is the kind of problem that fascinated him.

A conference was held at SISSA from 13 to 15 April 1992, to celebrate his 65th birthday, under the title ‘The renaissance of general relativity and cosmology’. The proceedings were published as a book by Cambridge University Press (Ellis et al. 1993). He was a major presence on the Italian astrophysics and cosmology scene. However, during this time he continued returning to Oxford, working in the Astrophysics subdepartment and at Wolfson College, and it was there that he died in 1999. His funeral was held at Wolvercote Cemetery, in Oxford, in accordance with Jewish rites.

CONCLUSION

Overall, Dennis made a major contribution to the development of relativity theory, cosmology and astrophysics during the period he so appropriately named as its renaissance. Cosmology in particular was treated with disdain by most physicists before the 1960s; it is now regarded
as a mainstream branch of physics, as is demonstrated by the inclusion of cosmological data in the Particle Physics Data Groups’ annual reports in the past decades. Dennis’s insistence on approaching these topics in a deeply grounded physical way had a significant role in this change. Furthermore, his three popular books (The unity of the Universe (6), The physical foundations of general relativity (16) and Modern cosmology (19)) and his public talks were very influential in enthusing many about physics in general and cosmology in particular; indeed, they were instrumental in persuading many now-famous scientists to enter these areas.

He was honoured as he Thomas Gold Lecturer at Cornell University (1990) and the Milne Lecturer at Oxford University (1991). He was elected a Foreign Member of the American Philosophical Society (1982), a Fellow of the Royal Society (1983), a Foreign Member of the American Academy of Arts and Sciences (1983) and a Foreign Member of the Accademia Nazionale dei Lincei (1984). In 1991 he was awarded the Guthrie Medal of the British Institute of Physics. He was President of the International Society of General Relativity and Gravitation from 1980 to 1984. A special issue of New Astronomy Reviews (F. Melchiorri et al. (eds) 2002) was dedicated to Dennis’s memory.

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In writing this biography, we found particularly useful sources in the oral history transcript by Weart (1978) and the biography by Smeenk (2007).

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