LEON MESTEL
5 August 1927 — 15 September 2017
Leon Mestel was best known for his wide-ranging work on cosmic magnetism, but he also worked on an equally wide range of non-magnetic problems in astrophysics, from star and galaxy formation to white dwarf cooling. Despite his work being primarily theoretical and highly mathematical, he was always aware of all the relevant observational data that both needed to be explained and also provided constraints for his theoretical models. He was internationally recognized as an authority on the influence of magnetic fields in astronomy, receiving a number of significant honours. He also had a deserved reputation for scrupulous honesty and integrity in his work. His life’s work culminated in the publication of two editions of a magisterial monograph on stellar magnetism. He collaborated widely, influenced many other researchers and was in great demand as a conference speaker. He was also a conscientious academic, taking his full part in departmental teaching and administration, and a delightful companion and friend to all who knew him. He was well known for his many stories and jokes, which were widely enjoyed. His outside interests included being a long-standing member of the Editorial Board of this publication, Biographical Memoirs of Fellows of the Royal Society.
Leon Mestel was born in Melbourne, Australia, on 5 August 1927, but his family moved back to England in 1931 and he spent most of his childhood in Forest Gate, East London; in later life he would refer jokingly to himself as an ‘East End guttersnipe’. He had an interesting family background, which certainly influenced his general outlook on life. His father, Solomon Mestel, was born in Galicia in 1886 and emigrated to England in 1908, eventually training to become a rabbi. He served as a minister in London 1919–1923 and 1931–1951, with service in Melbourne in between. He died in 1966, after a retirement devoted to translating Hebrew legal texts. Leon’s mother, Rachel Brodetsky, was also born in Eastern Europe, in the Ukraine, but was brought to England in 1893 at the age of 18 months; she became a teacher (as did two of her sisters). To quote Leon’s own description: ‘To avoid having to pay for a passport (an expensive and useless item), my grandmother crossed the Ukraine–Austrian border at night, suppressing with a shawl the crying of my mother which would have alerted the guards.’

One of Rachel’s brothers was Selig Brodetsky (1888–1954), who became professor in applied mathematics at Leeds 1924–1948, after studying at Trinity College Cambridge (starting a tradition followed by three generations of Mestels), and in Leipzig. He spent the war years as a lecturer in mathematics at the University of Bristol, where he also contributed to the war effort by advising a firm of optical instrument makers. His main academic interest was in aeronautics, on which he published a monograph as early as 1920. To quote Leon again, ‘His crowning achievement was appointment in 1949 as President of the Hebrew University of Jerusalem’ (37).* Sadly, heart problems forced retirement and led to his early death.

Rachel herself wrote her memoirs for the family after retirement, and lived until 1974. Her eldest brother lived to an even greater age, dying in Los Angeles aged 101 after a life as a family doctor in London, Winnipeg and Los Angeles; Leon used to visit his uncle when he happened to be in California, and always referred to him with fondness.

Leon was one of five children. His eldest sister, Jessica (Sharman), and brother, Vivian who died aged two, were born in England, while his other sisters, Norma (Brice) and Ruth (Hillel), were, like Leon, born in Melbourne. On his mother’s side alone, he had eight aunts and uncles, so he grew up in a large family and was steeped in the Judaic tradition. However, as he said himself (37), that tradition was complemented by a commitment to secular studies. His parents encouraged him towards learning in general and appreciation of music, literature and (to a lesser extent) visual arts, as well as stressing the need to become competent enough to earn his living. He developed an early interest in astronomy, but had not thought of becoming an astronomer, turning instead to mathematics rather than the traditional careers of medicine or law. When asked by his parents how he could make a living from mathematics, he replied that he could ‘always become a statistician or an actuary’ (37).

* References in this form refer to the short bibliography at the end of the text. We shall refer to Leon Mestel as ‘Leon’ in family and personal contexts, but as the more formal ‘Mestel’ in the sections on his work.
Leon Mestel

EDUCATION: SCHOOL AND UNIVERSITY

Leon’s first schooling was in Forest Gate, at Whitehill Place Elementary School (1932–1938), where he passed the scholarship examination needed for admission to West Ham Secondary School in Stratford (‘atte Bowe’, as he liked to say, deliberately quoting Chaucer). He and his two younger sisters were evacuated to Cornwall from June 1940 to July 1942, a period he recalled with fondness in later years.

It is possible that Leon was influenced by his mathematical uncle, but he certainly showed early promise in mathematics, in which he was encouraged by his mathematics teacher. His progress through secondary school was made possible by his sitting a paper on scriptural knowledge and thus winning a scholarship funded by the Samuel Gurney Educational Trust. He went up to Cambridge in 1945, again funded by scholarships—a state one based on his performance in the Cambridge Higher School Certificate examination (in mathematics, physics, and chemistry as a subsidiary), an Open Scholarship from Trinity College and a small subsidy from his local education authority. He flourished at Cambridge, becoming a Wrangler in the 1947 Mathematical Tripos, Part II, and obtaining a distinction in Part III in 1948. In addition to College prizes, he was also awarded a share of the Yeats Prize, ‘reserved for impecunious scholars’ (37).

Leon remained at Cambridge as a research student from 1948 to 1951. Despite having enjoyed Part III lectures on fundamental physics by Paul Dirac FRS, Nick Kemmer (FRS 1956) and Hermann Bondi (FRS 1959), he decided not to attempt research in those areas. He had also attended lectures by Fred Hoyle (FRS 1957) on statistical thermodynamics, which showed him that astrophysics was a fruitful area for the application of theoretical physics, and he started his graduate work under Hoyle’s supervision. His PhD was awarded in 1952 for a thesis with the modest title ‘Some problems of stellar structure and evolution’, thus laying down the foundations for his life’s work in theoretical astrophysics.

OVERVIEW OF CAREER

Mestel’s initial work focused on applying microscopic physics to the properties of stellar interiors, but he steadily extended his interests to include macroscopic effects such as rotation, large-scale circulation, accretion and stellar and galactic winds. He soon also included the effect of magnetic fields, the topic that would engage him for most of the rest of his life and for which he is probably best known. His first work in that area was in the field of star formation in 1955, a topic on which 10 years later he published a pair of comprehensive reviews. Major contributions to astrophysics included the introduction of the concept of ambipolar diffusion of a magnetic field in a lightly ionized gas, which was highly relevant to star formation. He later independently published and developed what became the canonical model of magnetic braking of a rotating star. He was also well known for his analysis of the interaction of magnetic fields and internal circulation within stars and for his masterful approach to the complex problem of pulsar magnetospheres.

His first postdoctoral position was as an ICI Research Fellow in the Department of Mathematics at the University of Leeds, where his uncle had been a professor until the previous decade. At the beginning of his Selig Brodetsky Memorial Lecture, given in Leeds in May 1982 (22), he tells a story about his move to Leeds. ‘I recall telling my late uncle
Brodetsky in 1951 that I had been appointed to a postdoctoral position at Leeds, but I had to say that I was not going to Leeds out of family loyalty. To this he replied: “Of course not, you are going there to work with Cowling.” Certainly I never looked back after this move; it was the second most intelligent thing I did, second only to my marriage, which also took place in Leeds.’ There he worked for three years with Tom Cowling FRS, one of the pioneers in cosmic electrodynamics, who was a significant influence on his subsequent research, although they never published a joint paper.

After Leeds he won a Commonwealth Fund fellowship, which took him to Princeton University Observatory for a year, during which time he interacted with Martin Schwarzschild (ForMemRS 1996) on stellar evolution and with Lyman Spitzer (ForMemRS 1990) on the physics of the interstellar medium; Spitzer was another major stimulator of his interest in electromagnetic effects in astrophysics. After Princeton, he moved back to Cambridge, holding a teaching position in the Department of Applied Mathematics and Theoretical Physics (DAMTP) and becoming a Fellow of St John’s College, where he remained until 1966, apart from one year back in Princeton as a visiting member of the Institute for Advanced Study. One of his undergraduate students in Cambridge, David Moss, later became a life-long collaborator. Mestel then spent another year as J. F. Kennedy Fellow at the Weizmann Institute of Science in Israel before taking up a chair of applied mathematics at the University of Manchester in 1967.

His next move was to Sussex (figure 1), where he was appointed professor of astronomy in 1973. He remained there until his retirement in 1992, but remained very active as emeritus professor at Sussex for another 25 years; he finally moved back to Cambridge in 2008, mainly to be closer to family, but he continued scholarly work and an interest in astronomy until the end of his life. His eighty-fifth birthday in 2012 was marked by a special issue of the Royal Astronomical Society’s magazine, Astronomy & Geophysics, in December (RAS 2012) to which he himself contributed an autobiographical account (37).

**EARLY WORK, AND NON-MAGNETIC PROBLEMS**

In 1950, while still a research student, Mestel published his first paper (1), on the thermal conductivity in dense stars. This led on to his first major paper (2), cited regularly throughout his life, which set out for the first time the details of the cooling mechanism for white dwarf stars. A later (1967) paper with Mal Ruderman (14) clarified the cooling model, noting the consequences of crystallization of the ions. He confirmed that it is essentially correct to speak of the white dwarf cooling at the expense of its thermal energy alone, a result so well-accepted that it is now used without reference to the original precise arguments needed to justify it. Prior to that paper with Ruderman, he had written an authoritative review of the theory of white dwarfs as a chapter in the Stellar structure volume (Aller & McLaughlin 1965), which was volume 8 of the planned comprehensive nine-volume ‘Stars & stellar systems’ series published by the University of Chicago Press (1960–1968 and 1975; volume 4 never appeared). He also worked on accretion, and on mixing by meridional circulation currents inside stars (e.g. (4)), a topic that he summarized in a second chapter in volume 8 of ‘Stars & stellar systems’.

Mestel’s interest in accretion, like his interest in mixing by circulating currents, began during his thesis work, when he looked at the question of what would happen to a white dwarf if it accreted matter from the interstellar medium (3). However, it developed in the
context of star formation and the general problem of what happens to a cloud of gas as it contracts under gravity. He summarized his work in two comprehensive and authoritative review papers in 1965 (10, 11). In the first paper he restricted himself to non-magnetic clouds and started by generalizing the original derivation of the ‘Jeans length’, the criterion for the onset of gravitational collapse in a uniform infinite medium, a derivation which he informally referred to as ‘the Jeans swindle’; his treatment allowed for non-uniform density in finite configurations of various geometries. He then introduced the problem of stability and finally considered the effects of rotation, outlining the so-called ‘angular momentum problem’. The aim of the second paper was to include the effects of magnetic fields, which will be discussed in the next section.
He had earlier considered a model for the angular momentum distribution in a disc galaxy as a result of gravitational contraction. He asked what would happen when an initially uniform-density spherical cloud in uniform rotation contracted with every element conserving its specific angular momentum, and found that if the density were strictly uniform the cloud formed a disc with uniform angular velocity, as is approximately true for the inner regions of the Milky Way and other disc galaxies. However, if the density is slightly non-uniform (following a simple law with radius) the resulting disc has the constant linear velocity law of galactic rotation seen in the outer regions of many spiral galaxies (9); this approximate model for a disc galaxy later became known as the ‘Mestel disc’. The following year (1964), he spent two months visiting MIT and formed a collaboration with C. C. Lin and F. Shu that led to a well-cited paper (12) on a related but different problem: the gravitational collapse from rest of a uniform non-rotating pressure-free spheroid. They found that the eccentricity increased during the collapse, and thus that the state of spherical collapse is singular: the slightest overall departure from sphericity is systematically magnified, so that in particular an oblate spheroid will collapse to a ‘pancake’. This result was taken up and made famous by Y. B. Z’eldovich (ForMemRS 1979) (Z’eldovich 1970) in the context of structure formation in the Universe (although Z’eldovich does not cite the Lin et al. paper). The paper does not allow for any effects that would occur in real clouds; in a later paper (13), he considered what would happen to sub-condensations in a differentially rotating disc-shaped cloud, a configuration relevant to planetary formation. He showed that the angular momentum of such a sub-condensation depended in both magnitude and sign, both on the law of rotation in the disc and on the geometry of the condensation, so that in some cases the spin may be retrograde relative to the disc spin (cf. Venus in the Solar System).

A later collaboration with Rudolf Kippenhahn, Dan Moore and Judith Perry led to two more papers (20, 21) on non-magnetic problems, this time analysing radiation-driven winds from quasars and active galactic nuclei. The first paper considered steady winds, finding that they are parameterized by the luminosity-to-mass ratio and by the fractional mass loss rate; the second paper showed that spherically symmetric winds are in general unstable, except when expanding at near relativistic speeds.

In his work on meridional circulation, Mestel (4) considered the problem of mixing in rotating stars, extending significantly work by Sweet (1950). As had been shown long before by Eddington (1926), the departure from sphericity caused by rotation disturbs thermal equilibrium and drives circulation currents in meridian planes to compensate. Sweet’s analysis showed that Eddington had grossly overestimated the flow velocities of these currents, but argued that a uniformly rotating early-type star would still be sufficiently well mixed to remain chemically homogeneous during its evolution. Mestel went one stage further, recognizing that the currents themselves would cause a non-spherical distribution of chemical composition by mixing material out of the core in a latitude-dependent way. This would in turn cause a departure from thermal equilibrium that would drive currents that opposed the effect of the rotationally-induced currents. These so-called ‘μ-currents’ would therefore choke off the rotational currents and prevent significant chemical mixing between the core and envelope. Later calculations of stellar evolution by others confirmed that the evolution of unmixed stars fitted observations better than the evolution of chemically homogeneous stars. Even in this paper, where magnetic effects do not appear in the equations, they are tacitly present to maintain the model star in uniform rotation.
Leon Mestel

COSMICAL MAGNETISM

Mestel’s research interests centred on the broad field of stellar magnetism, as treated in his final magisterial volume (38), published by Oxford University Press. The original edition of this book, published in 1999 (35), was superseded by the second edition of 2012 (38). This covered much of the same material in greater detail, but the section on pulsars was omitted and replaced by a longer treatment of the role of magnetism in star formation. This field emerged in his own lifetime and he played a major part in its development, both through his own research and through his influence on students and younger colleagues.

In his book Mestel gave a superb overview of the area. His own original work tackled interactions between magnetic fields and electrically conducting fluids, notably ionized gases and molten metallic conductors, but it reflected his wide interests in astrophysics and cosmical magnetic fields. Mestel’s own research relied on analytical approaches and, as befitted a well-trained mathematician, he displayed prodigious skill in handling the complicated nonlinear equations that governed the rich behaviour of magnetic fields in electrically conducting fluids, whether molten metallic conductors (as in the Earth’s core) or gaseous plasmas (as in the Sun, other stars and the interstellar medium). Despite his rigorous mathematical approach, he always tried to understand first the basic physical processes involved in a situation, so that he could make appropriate simplifying assumptions that would allow him to model it in a tractable way that still contained the essential physics of the problem.

Mestel followed his mentors, Cowling and Hoyle, in focusing on major issues rather than on minor patterns of behaviour. As mentioned above, his life’s work was reviewed by younger colleagues in a special celebratory issue of Astronomy and Geophysics (RAS 2012).

In what follows, we look first at the maintenance of global magnetic fields by dynamo processes in stars (like the Sun) and in planets (like the Earth). Progress here has been led by observations, on the one hand of sunspots and their associated magnetic fields in the Sun, and on the other by measurements of the geomagnetic field. G. E. Hale (ForMemRS 1909) had shown that sunspots were the sites of strong magnetic fields that varied cyclically and reversed on a typical timescale of about 11 years (Hale 1908). On the other hand, it gradually became apparent that the Earth’s magnetic field is generated by motion in its molten metallic core, and palaeomagnetic measurements have shown that it reverses irregularly on a much longer timescale.

In due course, stellar observations revealed a wide variety of magnetic behaviour in stars, depending on their internal structure and on the speed of their rotation. The Sun rotates with a period of about a month and its behaviour is typical of relatively slow rotators, but rapid rotators are far more active, gradually slowing down and growing magnetically less active as they age. Our Sun’s 11-year magnetic cycle is modulated by grand minima when its magnetic behaviour is drastically reduced—a pattern that is characteristic of a nonlinear oscillator. As the Sun ages, it will gradually spin down and eventually grow magnetically less active; but there are other families of stars that rotate far more rapidly, displaying more dramatic activity and more exotic variations in behaviour, governed (for stars of fixed mass) primarily by their rotation rates.

* NW wrote the first draft of the following broad overview of this area, concentrating on the second edition of Mestel’s long monograph on stellar magnetism, which NW read carefully and critically.
Mestel entered this field of research shortly after obtaining his PhD at Cambridge, when he moved to Leeds and came under the influence of Cowling, one of the founding fathers of magnetohydrodynamics. Indeed, stellar magnetic fields remained central to his interests for the rest of his career, culminating with the publication of his major book, *Stellar magnetism*, which appeared in its final form during the last decade of his long life (38). In the course of his career, Mestel trained and influenced many younger scientists in this field of study, imbuing them with his own high standards and his style of research (figure 2). We now review the main features of his research output, drawing on his many publications as well as on his own summaries of his achievements. His personal approach to research remained essentially analytical, rather than relying on computation, although he did on some occasions collaborate with colleagues who would make any necessary calculations. However, he did successfully follow the numerical approaches of others in describing the maintenance of global magnetic fields by nonlinear hydromagnetic dynamo action. These aspects of his research interests are described in his final book along with other related topics involving cosmical magnetic fields. His own publications are mirrored in the output of a distinguished array of research students, starting with Donald Lynden-Bell (FRS 1978) and continuing with the work of a whole generation of others whom he influenced, including Kumar Chitre, David Moss, Ian Roxburgh, Andrew Collier Cameron, David Hughes, Chris Jones and ourselves.

The major topics that he engaged with—meriting chapters in his book—began with general studies of magnetic fields in stellar interiors, and focused successively on stellar winds and magnetic braking of stars’ rotation rates and then on late-type stars (exemplified by the Sun) and stellar dynamos. He published more papers on early-type magnetic stars than on any other single topic, closely followed by his work on the role of magnetic fields in star formation. Our review of his achievements follows this arrangement, concentrating on particular aspects where his own contributions had the greatest impact.

**Stellar magnetism**

We give here essentially a review of Mestel’s monograph (38), on the grounds that it encapsulates much of his own research and there is no better summary of his life’s work.

We focus on particular aspects where theory and observations interacted most successfully. As noted above, his research centred on interactions between magnetic fields and electrically conducting fluids—notably ionized gases and molten metallic conductors. Trained as an applied mathematician, his own work was theoretical and primarily mathematical, but it reflected his interests in astrophysics and in the magnetic properties of stars and planets. Mestel exhibited considerable versatility and skill in tackling complicated problems by employing analytical techniques.

The basic mathematical structure of magnetohydrodynamics depends on a combination of Maxwell’s equations (describing the electromagnetic field) with the equations governing fields in an electrically conducting fluid, whether an ionized gas or a liquid. Mestel’s book on stellar magnetism (truly a magnum opus) covers a vast range of hydromagnetic behaviour, but we can only concentrate here on the most significant and fundamental aspects of magnetic activity in different types of stars.

The first three chapters of the book survey relevant aspects of magnetic behaviour, focusing on properties of conducting fluids and on the interactions between magnetic fields, convection and rotation, and concluding with an analysis of magnetohydrodynamic dynamo action. A key result here is Cowling’s theorem that a purely axisymmetric magnetic field cannot be
maintained by a hydromagnetic dynamo. It follows that any globally axisymmetric magnetic model can only be a (possibly convenient) idealization. This limitation naturally complicates theoretical investigation, especially when the effects of rotation are included.

Idealized models of magnetoconvection focus on the resulting ‘dynamo problem’. Mestel summarizes calculations by Dudley & James (1989) and Moss (2008), who demonstrate dynamo action by a single axisymmetric roll plus differential rotation. More generally, Parker (1955) proposed that the macroscopic average of small-scale fluctuations could lead to an extra source term (the $\alpha$-effect) in the magnetic induction equation. Further ramifications of magnetohydrodynamic dynamo theory are analysed in chapter 6 of Mestel’s book.
Chapter 7 is devoted to magnetic braking of stellar rotation by winds, with particular emphasis on oblique rotators and the solar wind. The following chapter treats late-type stars in general but focuses on the solar dynamo, emphasizing its influence on the Sun’s rotation and the role of the solar tachocline. This is followed by a discussion of the solar–stellar connection and the effects of rapid rotation on stellar dynamos. Next comes an account of the magnetic properties of early-type stars, starting with non-uniform rotation and oblique rotators and concluding with a discussion of their magnetic fields.

The remaining three chapters of his book deal first with pre-main sequence evolution and the formation of magnetized accretion discs, with their own dynamos and associated centrifugal winds. Mestel concludes this chapter by quoting a prophecy by Subrahmanyan Chandrasekhar FRS, ‘that it is the usual fate of cosmogonical theories not to survive’, but nevertheless he himself prophesies that ‘cosmical magnetic fields will continue to play a central role in future theories and, in particular, the magnetohydrodynamics of discs and the associated winds and jets will continue to be a thriving industry’.

Last of all, Mestel turns to the role of magnetism in star formation, concentrating on the classical and weak-line T Tauri stars, as precursors to the main sequence. Following Hoyle, he first introduces the critical Jeans mass $M_J$; next, he develops a cloud model—first spherical and then spheroidal—before going on to discuss magnetic braking of rotating clouds and the effects of flux leakage.

The book concludes with a discussion of magneto-gravitational equilibrium in a rotating disc model, generalized to represent a magneto-turbulent cloud, and a consideration of flux leakage, followed by a final summing up of the expected structure of large-scale galactic magnetic fields—altogether an ambitious termination.

_Mestel’s own research in cosmical magnetism_

One of Mestel’s abiding interests was in the origin of magnetic fields in stars: are they a fossil remnant of star formation from a magnetized cloud, or are they formed as a result of dynamo action? This is, as he foresaw, a topic still under active investigation (see, e.g., Wurster et al. 2018), with the balance now shifting towards dynamo action. He returned to this topic throughout his career, and his final research paper (36), with his long-term collaborator David Moss, constructs an approximate analytical model of the evolution of a stellar magnetic field that displays clearly the underlying physical processes. The evolution occurs as a result of the combined effects of ohmic decay and the thermally-driven dragging of flux by the magnetic analogue of the Eddington–Sweet circulation familiar in non-magnetic rotating stars. The model agrees qualitatively with detailed numerical simulations by others.

However, Mestel’s interests in magnetic fields in an astronomical context covered a much greater range than just the origin of stellar fields, and we have tried to cover some of his specific achievements by dividing them into three broad fields.

(a) _Star formation and the interstellar medium_ 

As noted above, early in his career Mestel became interested in problems of star formation, summarizing his ideas in two seminal review articles. In the second of these (11), he tackled the effects of magnetic fields on a contracting gas cloud, discussing for illustration the gravitational instability of a uniform-density cloud in the presence of an initially uniform magnetic field. It is assumed that the magnetic field is ‘frozen in’ to the gas (i.e. the conductivity is infinite). One of his key points is that the presence of a magnetic field solves
the angular momentum problem: how does a rotating, collapsing cloud avoid turning into a
disc, with collapse halted perpendicular to the rotation axis? The magnetic field can remove
angular momentum, allowing the cloud to contract to proto-stellar densities. To accomplish
angular momentum loss, the frozen-in assumption has to be relaxed, which happens because
the field becomes distorted, and reconnection occurs.

Mestel had already realized a decade earlier the importance of relaxing the assumption
of strict flux-freezing in the low density gas in the interstellar medium. With Lyman Spitzer,
during his year in Princeton, he wrote the paper (cited more than 500 times) that introduced the
concept of ‘ambipolar diffusion’ of a magnetic field in a lightly ionized gas into discussions of
star formation (6). This concept has been widely accepted and used, but it is only very recently
that the possibility of directly observing the effect has arisen (Lankhaar & Vlemmings 2020).

Mestel did not publish a large number of papers on star formation, but he retained a keen
interest in the subject, and often spoke at conferences; RCS remembers him making critical
comments on other people’s work at conferences when he believed that an author had made
an unwarranted assumption or approximation—sometimes sotto voce to a close neighbour in
the audience, but at other times quite loudly to the speaker!

His approach was very much that of trying to understand the basic physics of situations
by constructing simple models, for example in the interaction of magnetic forces with other
forces, such as gravitation. He wrote several papers (e.g. (23,29)) considering simple models
of gaseous discs in magneto-gravitational equilibrium; neither of the papers (23) and (29) is
immediately applicable to stars, but they do give a clear insight into the interaction of the
forces. The model in the 1990 paper (29) may also possibly represent certain observed disc-
like structures (e.g. Sargent et al. 1988), although he was careful to stress that his model did
not contain all the physical processes (e.g. Alfvénic turbulence) that are likely to be present
in a real disc. In a related paper with Campbell (26), he considered the case of star formation
in a disc with orthogonal rotation and magnetic axes, which is discussed in more detail in the
next section.

The models all assume a background galactic field, and Mestel was also interested in the
origin of that field, publishing two papers with Kandu Subramanian (31, 32) on a dynamo
origin. Both papers study the interaction between the dynamo equations and spiral density
waves, using two different approximations, and demonstrate that there are rapidly-growing
bi-symmetric magnetic modes that are closely correlated with the spiral density waves and
co-rotate with them. The 1991 paper (31) also suggests that interaction with turbulence can
lead to a self-sustaining dynamo; later papers by others have modified the detailed picture, but
confirmed that a self-sustaining dynamo is indeed possible by invoking the magneto-rotational
instability (Fricke 1969; Balbus & Hawley 1991; see also (38) sections 10.5.2 and 10.6.2).

(b) Magnetic stars and related topics

Perhaps Mestel’s most interesting early work is a short one-page research note discussing the
principle of magnetic braking (7). He later developed a full theory of the process (16–18);
this was later extended in collaboration with Henk Spruit (25) and is now widely used in
magnetic braking discussions. The key point about the first 1968 paper (16, cited more than
450 times), which treats the case of aligned magnetic and rotation axes, is the realization
that there is a critical point on each field line where the stellar wind speed equals the Alfvén
speed. The loci of these points defines a surface that divides the outer wind zone from an inner
dead zone. It is only the wind zone that contributes to braking, because in that zone the wind
is strong enough to drag the field along and each element conserves its angular momentum rather than any longer co-rotating with the star. The other 1968 paper (17) extends the theory to non-aligned axes, while the 1970 paper (18) discusses the effect of the braking on the angle between the axes. The paper with Spruit in 1987 (25) explores how the effect changes with changing rotation rate and magnetic field strength.

In the related paper with Campbell (26), in the area of star formation, the authors studied ‘the evolution of a rotating, cool, self-gravitating gas cloud, permeated by flux from the local galactic magnetic field, and with the magnetic and rotation axes mutually orthogonal’. Contraction of the cloud will occur if the flux-to-mass ratio is below a critical value, but fragmentation (leading potentially to star formation) will occur if strict flux-freezing is relaxed and there is significant flux leakage. Fragmentation will cease when the optical depth of a fragment is of order unity. However, if flux leakage occurs only by ambipolar diffusion, the resulting fragment masses are many times a typical solar mass. The authors suggested that a more efficient leakage mechanism must be present, involving some form of dynamical dissipation, perhaps driven by hydromagnetic instabilities.

Much earlier (5), in a brief note written during his visit to Princeton, Mestel had considered how a magnetic field might decay in a proto-star, following this up a decade later by two detailed papers (13, 15) drawing on the idea of ambipolar diffusion (6). These considered a gas cloud contracting with strict flux-freezing (13) and the effects of relaxing flux-freezing (15) by ohmic diffusion rather than by ambipolar diffusion. The latter is much faster, but even so not fast enough to detach the field from the contracting cloud on a useful timescale. A promised third paper on what might lead to complete detachment seems never to have been published, perhaps because at this time his interests turned to pulsar magnetospheres (see below).

However, he did continue to explore the generation and evolution of magnetic fields in stars, moving from the possible thermal generation of the field (8) through to collaborations with Moss and R. J. Tayler (FRS 1995) on the evolution of fields in rotating stars. For example, their paper in 1990 (30) showed that the presence of magnetic torques was sufficient to enforce nearly uniform rotation of a star (see also (36), mentioned earlier). In addition, he spoke about the topic at many conferences.

(c) Pulsar magnetospheres

When it was first realized that pulsars were spinning neutron stars with very strong magnetic fields, Mestel had already been working on rotating magnetic stars, and extended the Goldreich & Julian (1969) proposal of a dense pulsar magnetosphere to the oblique rotator model on which he had been working in the context of stellar braking (19). This was the start of almost an obsession with the magnetosphere problem. He used to describe the physical set-up informally as ‘a classic Part III problem’ (referring to the Cambridge Mathematical Tripos), and was constantly frustrated by its difficulty. In the preface to the first edition of his monograph Stellar magnetism, he says that ‘... it is just intolerable that we should not understand how a rotating magnetic neutron star ... is able to come to terms with its environment’. We follow the structure of the broad-ranging presentation of the field in the first edition, but making particular reference to work he himself contributed (as noted above, in the second edition the pulsar chapters were omitted to allow space to expand the other sections).

Interestingly, the genesis of the field came in a paper by Pacini (1967) that preceded the discovery of pulsars, and was itself based on earlier work by Stibbs (1950) and others on the oblique rotator model of variations in magnetic stars with much weaker fields.
Thomas Gold FRS (Gold 1969) quickly used this model, together with the observed energy loss from pulsars deduced from the rate of slowing down, to estimate the surface field of the rotating neutron star as $ca 10^{12}$ G. The initial models were of a rotating magnetic neutron star in a vacuum. However, Peter Goldreich (ForMemRS 2004) and W. H. Julian (Goldreich & W. H. Julian 1969) soon pointed out that this was not self-consistent: assuming that the internal field extends into the surrounding vacuum, it follows that there is a surface charge and an electric field component normal to the surface that is amply strong enough to overcome gravity and drive the charge outwards. A dense charged magnetosphere soon results. As indicated above, Mestel’s first contribution (19) was to extend this axisymmetric model to an oblique rotator model, in which the rotation and magnetic axes are inclined to each other. The majority of his own later research, however, concentrated on aligned pulsar models (e.g. (24, 27, 28)), which are more amenable to detailed treatment and illustrate the essential physics.

One of the key features of all models is the importance of the light cylinder (l-c), where the co-rotation speed reaches the speed of light. Beyond the l-c, charges in the magnetosphere can no longer remain on co-rotating field lines, and this causes an electrically driven wind of particles (electrons or ions) that carry away the angular momentum built up while moving out on field lines within the l-c. In the 1999 monograph (35), Mestel distinguishes between the ‘classical’ model (chapter 13), which omits quantum effects, and the more realistic model, where pair production is included (chapter 14). In the classical aligned model (with aligned rotation and magnetic axes), electrons ‘leave the polar regions as a sub-relativistic stream, picking up energy from the electric force and angular momentum from the magnetic torque’ (35) (all direct quotations are from the relevant chapter). At the l-c, dissipative effects start to matter and the electrons drift across field lines and begin to radiate; they eventually complete a circuit back to the star at a lower latitude in the same polar cap, so there is no net charge accumulation. However, his simple model is charge-separated, with electrons in the polar cap and ions within the field lines that close within the l-c; the two zones are separated by a wedge-shaped vacuum gap (although the returning electrons do traverse the gap, so it is not completely empty). In the final section of chapter 13, he applies the details of the aligned model qualitatively to the oblique rotator model and in particular to the perpendicular rotator (34).

Mestel notes in the beginning of his chapter 14 that ‘the only energy sources are the potential variations set up on the surface by the rotation of the star in its magnetic field’ and that ‘the magnetospheric currents complet[e] their circuits by crossing field lines ... beyond the l-c’. This and other global constraints are the basis of the classical model. However, it predicts that the energy lost beyond the l-c is in the form of gamma-rays (e.g. (24)), whereas when relativistic effects are included electron–positron pairs are produced. This qualitatively alters the model, and the relativistic model that he develops in chapter 14 has a strong electric field parallel to the magnetic field lines, strong enough to accelerate electrons to extremely relativistic values ($\gamma$ values of more than 100) as they flow out along the dipolar field lines. The detailed model that results depends on what is assumed about the boundary conditions at the surface of the star and at ‘infinity’ (i.e. well beyond the l-c).

Mestel also discusses general relativistic effects, which can, but need not, produce significant changes in the special relativistic models, again depending on what boundary conditions are chosen and also on the angle between the rotation and magnetic axes. He discusses these models in great detail (see, e.g., the model of Mestel & Shibata (33), described in section 14.5 as ‘the first attempt to construct self-consistent models’), and his masterly
synthesis of work in this area, by himself and other people, is his lasting contribution to the theory of pulsar magnetospheres.

**RESEARCH STUDENTS AND COLLABORATORS**

Leon was a stimulating and challenging supervisor to some 20 research students, but he found his first research student, Donald Lynden-Bell, who himself became a formidable mathematician, challenging. RCS was told by Roger Tayler that, soon after Lynden-Bell started, Leon had gone to Tayler in some despair, saying ‘I have this new research student, and he won’t do anything I ask him to do’. Tayler said that he told him not to worry—Lynden-Bell would find his own problem, which he duly did. His other students included (in alphabetical order) Dale Barker, Alan Cousens, John Faulkner, Richard Fitzpatrick, Li Jianke, Teresa Lago, Richard Paris, Pat Phillips, Ian Roxburgh, C. S. Selley and Peter Strittmatter. Leon also had many collaborators (see e.g. figure 3). To quote again his autobiographical account (37): ‘my list of students (undergraduate and graduate) and collaborators includes: D M Barker, D Biront, R R Burman, C G Campbell, S M Chitre, A Collier Cameron, A Cousens, J Faulkner, R Fitzpatrick, K C Freeman [FRS 1998], D J Galloway, J Gillis, S P Goodwin, M Goossens, D O Gough [FRS 1997], L Jianke, J Kuipers, T Lago, D Lynden-Bell, A J Mestel [his son Jonathan], P Phillips, M A Raadu, J A Robertson, I W Roxburgh, R C Smith, P A Strittmatter, R J Tayler, H Tunmer, Y-M Wang, N O Weiss and K C Westfold.’ Surprisingly, the list does not include one of his longest-standing collaborators, the late David Moss (1943–2020), who was taught by Mestel in Cambridge but took his DPhil with Roger Tayler at Sussex, finishing there before Mestel moved to Sussex. (During Moss’s Part III year in Cambridge, Leon offered him a place to do a PhD with him in Manchester, but he had already accepted the Sussex place.)

**PEOPLE WHO INFLUENCED HIM**

After his PhD supervisor, Fred Hoyle, the first person who became a key influence on Leon’s subsequent research was Tom Cowling in Leeds, while in Princeton he interacted with both Martin Schwarzschild and Lyman Spitzer Jr. Both Cowling and Spitzer stimulated his lifelong interest in electromagnetic effects in astrophysics, and might be thought of as setting him off on his life’s work.

In 1982 Leon was invited to attend a meeting at the Max Planck Institute of Physics in Munich—celebrating the seventy-fifth birthday of Ludwig Biermann—to give a talk (see figure 2) entitled ‘Ludwig Biermann’s influence on astrophysics—a personal view’. RCS has a copy of his text, which contains some interesting personal comments in his introductory remarks, which he gave in German. A free translation reads:

I have for many years regarded myself as Ludwig Biermann’s academic nephew. The reason is that Professor Tom Cowling is my academic father, and that in the eyes of the whole astrophysical community Tom Cowling and Ludwig Biermann are like brothers. When I showed him my invitation, my colleague Roger Tayler said ‘Remember that you are there as Tom’s representative’.

He then went on to say that ‘in the following generation, Rudi Kippenhahn and I are at least cousins and perhaps even twins’. Leon and Kippenhahn shared research interests, but also
jokes and stories—Leon always brought new stories back from visits to Kippenhahn (and to many other friends around the world) and shared them at Sussex coffee times, to everyone’s delight.

More academically (and now in English), he pointed in his lecture to several key insights made by Biermann. Examples are the Biermann battery effect in connection with the origin
of magnetic fields and Biermann’s work (paralleled by Cowling) on convection in stars (including the possible effect of non-isotropic turbulence), in particular the role of convection and magnetic fields in sunspots. He also mentioned Biermann’s paper (Biermann 1951) treating cometary tails as diagnostic of what we now call the solar wind, whose influence on the magnetic braking of the Sun was later the subject of one of his own papers (16).

In his own autobiographical account (37), Leon also mentions having ‘fruitful interactions’ with many others, including ‘R D Blandford [FRS 1989], H Bondi, S Chandrasekhar, F D Kahn [FRS 1993], M McIntyre, W H McCrea [FRS], C F McKee, D B Melrose, E C Ostriker, E N Parker, E R Priest [FRS 2002], M J Rees [PRS 2005–2010], P A Sturrock, A Toomre, J Toomre, V Trimble and E G Zweibel’ (figure 4). Not mentioned in that list, but certainly well known to him, is E. A. (Ed) Spiegel, another source of the jokes and stories for which Leon was famous, who is also quoted as having once heard Leon describe magnetic fields as ‘the great simplifying force in astrophysics’.

CONCLUSIONS

Leon Mestel was a mathematician by training, but one with a great physical instinct that enabled him both to recognize an interesting problem in astrophysics and to understand the physical essence of it. He could then formulate it in a way that was both mathematically tractable and physically sufficiently realistic to be tested against observation. He had a warm, friendly nature that made him many friends, and he was essentially modest, but he was also rigorous in his approach to his work and could be impatient with those whom he suspected of being less careful than himself, although he was very willing to advise and help younger colleagues.

FAMILY AND WIDER INTERESTS

While a research student at Cambridge, Leon met Louise, daughter of Stanley and Louisa Cole, who was studying psychology (and later worked in social sciences research). They married in 1951 and had four children Leo (b. 1953), Jonathan (b. 1957), Rosie (b. 1959) and Ben (b. 1960). Leo is now a consultant psychiatrist in Ireland, Rosie a science journalist in California and Jonathan and Ben are academic mathematicians in the UK. Leon was very much a family man and a generous host. RCS (who was a close neighbour of the Mestels in Sussex) remembers with pleasure parties at his home with many friends and neighbours spread out through the large house and many noisy conversations going on, as well as quieter personal visits.

Brought up in the Judaic tradition, Leon had many Jewish friends and observed the main festivals, although he only rarely attended the synagogue. He read widely on many subjects, had a large collection of books, and spoke or understood several languages. He also enjoyed classical music, and there was often music in the house. He travelled extensively, despite a dropped right foot arising from childhood polio that made walking progressively harder as he got older.

Leon spent several extended periods overseas, some of which have been mentioned above. In 1961–62 he spent the academic year in the USA, visiting Stanford and Princeton and being principal lecturer at the Summer School of the Woods Hole Oceanographic Institution in Massachusetts. In 1964, he held summer visiting positions at MIT and at the Institute of Space
Studies in New York. In 1979–80 he spent a sabbatical year in Europe, with visiting positions at Nordita, Copenhagen, MPI für Astrophysik, Munich, and Sterrewacht Leiden. Between 1968 and 1999 he also made a variety of shorter visits to the USA, Australia, Canada, India, Belgium, Japan, Israel, The Netherlands and New Zealand.
In among these activities, Leon found time to serve two terms on the Council of the Royal Astronomical Society (RAS), to be president of Commission 35 (Stellar Constitution) of the International Astronomical Union, to be several times a member of astronomy committees of the Science and Engineering Research Council and to serve two terms as a member of two different sectional committees of the Royal Society, as well as being a long-standing member of the Editorial Board for Biographical Memoirs.

He received several honours, including a number of scholarships during the course of his education and the joint award of the Yeats Prize at the end of his BA in 1948. In addition to Fellowship of the Royal Society, he was awarded the Eddington Medal and the Gold Medal by the Royal Astronomical Society. He was a member of both the RAS and its dining club. As well as the Brodetsky and Biermann lectures mentioned above, in 1966 he gave the Racah Memorial Lecture in Israel and the Roger Tayler Memorial Lecture in 1999.

During the course of writing this memoir, RCS has been told several stories about Leon. Perhaps the most unexpected is the one about the well-known film director Bryan Forbes, who went to the same secondary school as Leon and was also evacuated to Cornwall. They became good friends, and one of the Sussex post-docs, Chris Campbell, recalled Leon telling him ‘that there had been a horrible murder in the area, so they changed the title of Red sails in the sunset
to *Blood stains on the carpet* and the title of *When I grow too old to dream* to *When you grow too old to scream*’. On a less gory note, several people recalled his passion for fruit. One of the Astronomy Centre secretaries, Hazel Freeman, remembered his orange eating—he often had a whole pile of oranges in his office, which generated a not-unattractive aroma that spread out into the secretaries’ office. She says he bought them in bulk, at her suggestion. One of the lecturers, Nigel Holloway, said: ‘One of the non-academic things I learnt from Leon was how to eat 99% of an apple, leaving only the stalk and pips. Before Leon, I hadn’t seen anyone do that.’

When the time came to move to Cambridge, to be closer to family, all his children came to help him downsize. Early on in their time in Sussex, Louise was a lovely co-host, but sadly gradually developed chronic back problems, which towards the end made her almost bedridden. She died in February 2014 and was buried in the Jewish section of the Cambridge Cemetery. After Leon died, he was buried (figure 5) in the grave next to Louise in a ceremony attended by many friends and colleagues; there were also many appreciative tributes from colleagues and friends unable to attend.

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**AUTHOR PROFILE**

*Dr Robert Connon Smith*

Robert Smith was brought up and educated in Glasgow, where he obtained his PhD at the University of Glasgow under Professor Peter Sweet and then spent two years teaching in the Glasgow astronomy department. He spent the rest of his professional life in the Astronomy Centre at the University of Sussex, latterly as Emeritus Reader in Astronomy. One of his close colleagues at Sussex was Leon Mestel, who, by coincidence, had also been his supervisor for a year spent in Cambridge while Sweet was on sabbatical in New York. RCS shared many research interests with Mestel, working on rotating stars and mixing in single and binary stars, although not getting deeply involved in stellar magnetism! Later he switched his emphasis to observations of binary stars, where his group created some of the earliest simple maps of the cool stars in cataclysmic binaries. He also wrote an undergraduate textbook, *Observational astrophysics*, published by Cambridge University Press in 1995.
Professor Nigel Weiss

Nigel Weiss was born in South Africa and educated at Hilton College, Natal, before moving to the UK. There he attended Rugby School and then Clare College, Cambridge, where he later became a Fellow. His PhD, supervised by Sir Edward Bullard, started in seismology but turned to magnetohydrodynamics, which became his life’s work. After three years at Culham Laboratory he moved back to Cambridge, becoming professor in 1987. He is best known for his work on magnetoconvection in the Sun, where he made many fundamental contributions. He was also an excellent teacher and willing administrator. He had many interests outside astronomy, and was widely liked and respected. He was President of the Royal Astronomical Society (2000–2002), and received their Gold Medal in 2007. He was elected FRS in 1992.

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