"Gene": A personal tribute to the Life and Science of Eugene Newman Parker

Arnab Rai Choudhuri^{1,2}

¹Department of Physics, Indian Institute of Science, Bengaluru, 560012, India.

> ²Max Planck Institute for the History of Science, Boltzmannstrasse 22, Berlin, 14195, Germany.

Contributing authors: arnab@iisc.ac.in;

Abstract

This review provides a brief account of the life of Eugene Parker (1927– 2022) and discusses his contributions to plasma astrophysics. Growing up in Michigan, he went to graduate school at Caltech and then worked at the University of Utah before shifting to the University of Chicago, where he spent the rest of his illustrious career. Parker's most important scientific works are discussed in the context of the historical development of plasma astrophysics. In the study of the Sun, he made enormous contributions both to the MHD of the solar convection zone (including the formulation of turbulent dynamo theory) and to the understanding of the outer solar atmosphere (including the theory of coronal heating and the prediction of the solar wind). Parker's non-solar contributions include the Parker instability in the interstellar gas and the Parker limit of magnetic monopoles. We also try to convey an idea of Parker's highly individualistic personality and his very unique way of doing science.

Keywords: E. N. Parker, plasma astrophysics, MHD, solar physics

1 Introduction

Eugene Newman Parker—known simply as "Gene" to his friends and admirers—was arguably the most influential scientist in the field of plasma astrophysics. His passing away on 15 March 2022 at the age of 94 indeed marks

the end of an era when research in theoretical plasma astrophysics could be done with a certain elegance of style—at least by the masters of the subject. It was a style of performing elegant analytical calculations with simple models, formulated on the basis of deep physical insight, that would have far-reaching consequences in understanding important phenomena of nature. That style is perhaps possible in a subject only when its foundations are being laid down. It is disappearing in the field of plasma astrophysics with changing times as the subject is becoming more mature and technical.

Parker's creative career coincided with what I would call the heroic age of plasma astrophysics. When he started research in the early 1950s, the only astrophysical locations known to have magnetic fields were sunspots. It was during Parker's long career that different observational techniques established the ubiquitous presence of magnetic fields virtually everywhere in the astrophysical universe. On the theoretical front also, some of the first basic ideas of MHD had just been developed by Alfvén, Cowling, Elsasser, Chandrasekhar, Spitzer and a few others when Parker entered the field. It was expected that MHD would provide the key to understanding various cosmical phenomena, as indicated by the title *Cosmical Electrodynamics* of the classic monograph by Alfvén (1950). But it was still an expectation rather than a reality. Since the Sun happens to be a nearby (by astronomical standards!) large plasma body in which various MHD processes could be observed in detail, a major part of Parker's research output dealt with MHD processes in the Sun. However. Parker was very particular that he should not be regarded only as a solar physicist, but rather as an astrophysicist. When I was the Executive Editor of Research in Astronomy and Astrophysics and persuaded Parker to write a charming scientific reminiscence (Parker, 2014), he titled it "Reminiscing my sixty year pursuit of the physics of the Sun and the Galaxy". Parker was a humble and self-effacing man who rarely told people about his achievements. To the best of my knowledge, this is one of the only two accounts of his life and career in his own words that we have. The other one is the lecture he gave while receiving the Kyoto Prize, of which the transcript is available at the website:

https://www.kyotoprize.org/wp-content/uploads/2019/07/2003_B.pdf

We also refer to a journalistic account of Parker's life by M. Kaufman:

https://manyworlds.space/2022/04/12/nature-has-become-more-beautiful-physicist-eugene-parker-and-his-life-unlocking-secrets-of-the-sun/

and an obituary by K. Tsinganos:

https://baas.aas.org/pub/2022i039/release/1

The aim of the present review is to give an account of Parker's major scientific achievements along with a few words about his life and personality. I had the privilege of being his PhD student during 1981–85. However, as I started preparing this review, I realized that being Parker's PhD student does not automatically qualify somebody to write about his science. He made such wide-ranging and varied contributions in different aspects of plasma astrophysics that it is impossible for one person to fully understand the significance of all of Parker's works at a technical level, unless that person also happens to be almost as brilliant as Parker himself!

Rather than providing a catalogue of many of Parker's works, I shall focus on a few of his outstanding contributions. I shall try to give an idea of the historical contexts in which these works appeared and also describe how they influenced the subsequent development of the field. My aim will be to present a discussion of Parker's science in such a manner that it is accessible to any professional physicist rather than to experts of plasma astrophysics alone. When I discuss Parker's works on those topics of which my own knowledge is limited. my discussions will have to be somewhat superficial. It often happens in the case of creative geniuses in different spheres of human creativity (literature, art, music, science) that their most famous works eclipse their other almost equally important works. This happened to some extent in the case of Gene Parker. It is perhaps indisputable that the prediction of the solar wind was his most important work (Parker, 1958). However, some of his other works such as the formulation of the turbulent dynamo theory (Parker, 1955a) and the discovery of the non-equilibrium of magnetic topologies in stellar coronae (Parker, 1972) can hardly be considered less significant. At the time of writing this review. Web of Science lists about 2750 citations to the paper predicting the solar wind (Parker, 1958), whereas there are about 1620 citations to the paper laying down the foundations of dynamo theory (Parker, 1955a). A discussion of Parker's major contributions hopefully will give an idea of the breadth of his contributions. Since he had worked on almost all important aspects of solar physics and many important aspects of non-solar plasma astrophysics, this review provides a historical account of the growth of plasma astrophysics during 1950–1995 when Parker was active in research.

I shall try to give an idea of Parker's attitude towards science and the scientific community in a later section (section 8) of the review. However, it may be worthwhile to say a few words about Parker's style of science at the very beginning before we enter into a detailed discussion of his scientific contributions. What strikes one even from a superficial perusal of Parker's works is the high degree of individualism. I have rarely come across another scientist who was so little swaved by the scientific fashions of the day and had the courage to follow his own uncharted path of scientific investigations. Although scientific collaborations and multi-author papers were becoming the norm towards the later part of Parker's career, he mostly worked on his own. He also expected his students and postdocs to work on their own and to write single-author papers. He once told me that he never agreed to be a co-author in a paper unless he himself had repeated all the calculations in the paper on his own! Even though numerical simulations started becoming more common with the easy accessibility of computers and even though Parker always admitted the importance of numerical simulations, he himself never touched a computer for his research and fully depended only on the insights gained from analytical calculations. A

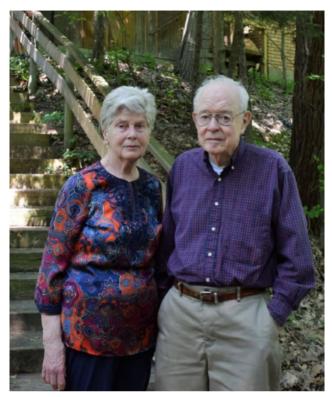


Fig. 1 Gene Parker with wife Niesje in front of their vacation home in Michigan on the day Gene turned 90. Credit: Eric Parker.

perusal of the acknowledgments of his various papers is particularly revealing. Parker was strongly guided by observations in his theoretical work and regularly discussed with observers about their new findings. Although he often thanked observers for useful discussion, he rarely thanked another theorist in the acknowledgments of his papers—especially in the later part of his scientific career. Parker's papers are always marvels of scientific composition and bear the stamp of a scientific autocrat who enjoyed doing science in his own terms. He would always pay particular attention to the logical structure of the paper. Since Parker often dealt with complex ideas years before others paid attention to them, it may not always be easy to read his papers. But a reader with the prerequisite technical knowledge can always follow the clear thread of scientific logic. Nothing would be fuzzy or obscure.

The next section will provide a brief sketch of Parker's early life and formative years. Then four sections will be devoted to Parker's contributions in his main research field of solar physics. In section 3, I shall make some comments about the general nature of Parker's works in solar physics and how they transformed the field. Then section 4 will discuss Parker's main contributions to the MHD of the solar convection zone (dynamo theory and magnetic buoyancy), whereas section 5 will highlight his contributions to our understanding of the outer atmosphere of the Sun (coronal heating and solar wind). Parker's various other important works related to the Sun will be briefly summarized in section 6. After these four sections, section 7 will be devoted to Parker's seminal non-solar works—mostly connected with the galactic magnetic field. In section 8, I shall try to present a pen portrait of Gene Parker as a scientist and as a man. Finally, I shall end with a few concluding remarks in section 9.

2 The formative years and the don at Chicago

Gene Parker was born on 10 June 1927 in the small town of Houghton in Michigan with a current population of about 8000. One can imagine that it was really a small town where his childhood years coincided with the Great Depression, which impacted American small towns in a manner depicted in the novels of John Steinbeck. The family, however, did not stay in Houghton, a copper mining town, for long. Gene's father Glenn Parker, who initially worked as a mines surveyor there, shifted to other jobs and eventually started working as an engineer for Chrysler, staying in the suburb of Detroit. There was a railroad yard nearby. Gene as a small boy was fascinated by the steam locomotive and wondered about its working principles (Parker, 2014). Gene's mother Helen, who had a BS degree in mathematics from Stanford University, did not pursue a career and raised three children, Gene being the eldest of the three. Some years later, when Glenn Parker had retired from Chrysler, he and Helen moved to the warmer Arkansas, where they developed a farm to raise cattle and chickens. There was no telephone in this farm in the 1950s. For many years, Gene Parker would write letters to his parents regularly. Luckily, the family has preserved these letters, which give a fascinating glimpse of the mind of Gene during some of the most important and creative years of his career.

Even in his boyhood, Gene displayed the rugged individualism of the American pioneer spirit. When he was barely 16, he used his earnings from summer jobs to buy a 40-acre wooded land in a remote location at the price of \$120. He and his younger brother built a log cabin there over the course of the next three summers—in the tradition of Thoreau building his log cabin near the Walden pond. Gene would have to ride a bicycle for 300 miles to go to his log cabin. After he passed away many years later and his body was cremated, half of the ashes had been buried in the wooded land near that cabin which still has no electricity or running water.

The USA in the days of Gene's youth was not yet the highly networked country which it became later. Long distance telephone calls would cost exorbitantly. People would travel across the country in buses and trains, since air travel was very expensive. Students went to colleges near their homes. Gene went for his BS to Michigan State University with a tuition scholarship. Although it was not a high-ranking university, Gene was lucky to have some

15 June

Dear Mother and Ded.

Thanks a lot for Ben Franklin's autobiography and "Who Blowed up the Qurchhouse". I have read the latter. And I can well believe that thestories are typical of the Ozarks. You can see many of the people at and around Dutton in the characters in the stories.

I guess the bignews around here is that I'll be getting married sometime around Thankspiving. Her name is Niesje Meuter (Né-shá Mú-ter), She is study "bacteriology and working on the polic project at the U. They have a big project where they give hundreds of kids shots and then take blood samples to see if the number of anti-bodies has increased. She is from the Netherlands and has been here for a couple of years. J've known herfor most of that time. Her folks also live in Salt Lake. Her father is an accountant. If the sun would shine sometime, I'll take a picture of her and send it to you. We're had several weeks of rain here and they have pretty well pulled out of the drought conditions.

Fig. 2 The beginning of Gene's letter to his parents dated 15 June 1954 informing them of his upcoming marriage in an unceremonious manner. This letter was written soon after Gene came to know that his younger brother had a son so that his parents had become grandparents. Credit: Eric Parker and Susan Kane-Parker.

extremely dedicated physics teachers who urged Gene to go for a top graduate school. Being not from a very well-off family, Gene had to save some money by working for six months as technician at the Chrysler lab in Detroit and then took a 72-hour Greyhound bus ride to Caltech, where he was a graduate student during 1948-51. Caltech did not give him any financial aid because people there did not know how to calibrate a grade report from a university in Michigan! Gene found Pasadena to be rather expensive and realized that his savings would run out in a few months. Luckily, he had done well in the quantum mechanics course taught by William Fowler, who later won the Nobel Prize for his work in nuclear astrophysics. When Fowler came to know that Gene was without financial aid, he immediately telephoned the Dean and insisted that this boy must be given a teaching assistantship (Parker, 2014). Gene survived in Caltech with that. His supervisor was H. P. Robertson, known for the Robertson-Walker metric in cosmology, who was working on other things at that time. He urged Gene to work out the theory of some structures observed in the interstellar medium. Gene's other mentor at Caltech was Leverett Davis, who interestingly was to work on an extension of Gene's model of the solar wind many years later (Weber and Davis, 1967).

After PhD, Gene worked for a few years at the University of Utah – first as instructor and then as research associate of Walter Elsasser. Gene always had a tremendous respect for Elsasser and regarded Elsasser as his real mentor who introduced him to the problem of astrophysical dynamos. Although Gene did some pathbreaking works in Utah, the authorities there felt that he was not doing interesting enough research and did not want to give him tenure. At that time, John Simpson was building state-of-the-art instruments at the University of Chicago to study cosmic rays and wanted to hire a theorist who could help them in selecting the right scientific questions to study. Chandrasekhar, Simpson's colleague at Chicago, suggested the name of Gene to Simpson. Gene came to Chicago in 1955 and remained there all his life, rising through the academic ranks and retiring in 1995. Gene served as Chairman of the Department of Physics during 1970–72 and as Chairman of the Department of Astronomy and Astrophysics during 1972–78. He was also the Chairman of the Astronomy Section of the National Academy of Sciences during 1983–86.

While at Utah, Gene met Niesje, who was to become his wife and life partner. Niesje grew up in the Netherlands, where her family lived through the difficult years of the Nazi occupation and then immigrated to Utah after World War II. With an initial training in bacteriology, she eventually got a job at the University of Chicago Graduate School of Business, rising to the position of Associate Director of Computing Services there. Gene and Niesje were married in Salt Lake City on November 24, 1954 shortly before they moved to Chicago. Their children—Joyce and Eric—were born in Chicago. Figure 2 shows a part of Gene's letter to his parents informing them of his impending marriage in an unceremonious way.

For many years, the family lived in a house at Homewood in the suburb of Chicago. When there would be an academic visitor whom Gene particularly admired, he would invite the visitor for dinner to his home with members of his group. I remember going for dinner to their home when Nigel Weiss and Henk Spruit visited. Many years later, when I visited Chicago from India, I had the honour of being the guest for whom Gene gave a dinner party. In some ways, Gene was the traditional husband who left the job of preparing the dinner to Niesje, an outstanding cook. However, Gene was the gracious host who would set the table and serve the guests. Gene himself never drank alcohol. I may mention that, when Gene's graduate student Tom Bogdan, a year senior to me, graduated, I gave a dinner party in my student apartment and invited Gene. Tom was a little alarmed that I had the temerity of inviting Gene to a typical grad student apartment, which was not in particularly great shape. But Gene and Niesje came and enjoyed themselves. Figure 1 shows Gene and Niesje taken on Gene's 90th birthday.

For several decades, Gene worked in the Laboratory for Astrophysics and Space Research (LASR), a building of modest size on the University of Chicago campus which housed the cosmic ray research group headed by John Simpson. However, two of the most beautiful corner offices in that building were occupied by two theorists: Chandrasekhar and Parker. In Figure 3 showing LASR, the



Fig. 3 The Laboratory for Astrophysics and Space Research (LASR) in the University of Chicago campus, where Parker had his office for several years.



Fig. 4 Gene Parker at different stages of his career: (i) As a graduate student at Caltech, and (ii) As a don at the University of Chicago.

upper left corner room was Gene's office and the upper right corner room was Chandra's office. It will probably be difficult to identify another building anywhere in the world from which so many outstanding contributions to plasma astrophysics originated. This building LASR was considerably restructured a few years ago. After Chandra's passing away, Gene wrote a review describing Chandra's contributions to MHD (Parker, 1996). Figure 4 shows photographs of Gene at two stages of life—as a university student and as a university professor. The photograph on the right side was taken by me during my student days. I particularly like this photograph, because looking at Parker standing in front of his huge collection of books and journals in his office, you get a feeling about the kind of scholarly scientist that he was. Gene's office was always in complete disorder—with piles of papers and books strewn all around. I often wondered how he managed to find anything in his office. Although Chandra and Parker were mathematical physicists of somewhat similar mould and were good friends, their personalities were totally different. Everything in Chandra's office would be perfectly ordered: every piece of paper in its correct place!

A teetotaller, Gene was a man of very simple and almost austere habits. He would usually commute by the Illinois Central train from his home in Homewood to the University of Chicago campus, although the train station was not exactly next door to the building LASR where we worked. Though he knew quite a bit about cars, he would drive only if he needed the car for something during the day. However, he allowed himself to indulge in one luxury. He always liked having personal copies of the books and journals he would look at for his academic work rather than consulting them in the library. In those pre-internet days when one would normally go to the library to look up journals, Gene had a personal collection of several journals, such as *Astrophysical Journal*, *Solar Physics, Geophysical and Astrophysical Fluid Dynamics.* One wall of his office was completely converted into a bookshelf where his books and journals were kept. One can get a glimpse of this personal library in the right side photograph of Figure 4.

After this account of Gene Parker's early life and scientific career, we shall now turn to his science in sections 3–7. I shall try to give a pen portrait of Gene as a scientist and a member of the scientific community in section 8, since such a pen portrait may be better appreciated by readers after knowing about his science.

3 Gene Parker and the growth of solar physics (and beyond)

Before describing the specific details of Gene Parker's works, I would first like to make a few overall comments about the way Parker transformed our theoretical understanding of various aspects of solar activity. A branch of science in which different important topics are interconnected through some unifying principles always possesses a special kind of intellectual appeal. Parker's monumental contribution to solar physics was to gradually build up over the years a grand edifice in which we can see the connections among the different aspects of solar activity, through the common thread of the magnetic field and its different manifestations in the solar plasma.

Instead of discussing Parker's works chronologically, let me highlight some of Parker's key contributions in a logical order best suited to illuminate the unified structure of the field solar MHD. Details of these works will be given in sections 4 and 5. The first central question is how magnetic fields arise in the Sun and other astrophysical bodies. Quite early in his career, Parker (1955a) formulated turbulent dynamo theory which provides an understanding of how magnetic fields may arise in regions of convection inside a rotating astrophysical body. Parker (1955a) also applied the basic ideas of dynamo theory to work out an ingenious model of the 11-year sunspot cycle. While today we may not agree with Parker's model of the 11-year sunspot cycle in all its details, it is indisputable that Parker's 1955 paper (Parker, 1955a) is the most influential paper in the history of dynamo theory and is still the starting point for anybody wanting to understand how magnetic fields are generated in astrophysical systems. The magnetic fields generated in the solar convection zone have to come to the solar surface and into the atmosphere. In the same year 1955, in

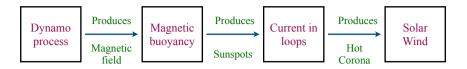


Fig. 5 The chain of causes-and-effects connecting different solar phenomena.

which Parker formulated dynamo theory, he also wrote the fundamental paper on magnetic buoyancy to explain why magnetic fields of the Sun (or rather parts of them) emerge from the Sun's interior through its surface (Parker, 1955b). The magnetic fields which emerge through the solar surface are the cause of various activities in the corona. When the theory of magnetic reconnection in the corona was being developed, Parker wrote a key paper giving rise to the idea of the so-called Sweet–Parker reconnection rate (Parker, 1957). A few years later, Parker (1972) discovered that coronal magnetic fields, while trying to relax to configurations of magnetostatic equilibrium, tend to produce many current sheets (i.e. regions of magnetic reconnection) in the corona, within which heat is produced by the conversion of magnetic energy. While this mechanism discovered by Parker may not be the sole mechanism for generating heat in the corona (magnetoacoustic waves dissipating in the corona may also contribute in a parallel mechanism), Parker's theory appears applicable for explaining the heating of the coronal magnetic loops, the hottest regions in the lower corona. Finally, the crowning achievement of Parker's illustrious career was to show that the hot corona would drive an outward plasma flow which he named the solar wind (Parker, 1958). This radical prediction was at first viewed in the community with scepticism and perhaps even disbelief, until support for it came from space observations within a few years. Remarkably, the prediction of the solar wind, which is caused by the hot corona, came several years before there was much understanding of what heats the corona.

Why do many of us consider Gene Parker to be the greatest solar physicist of our time—or perhaps of all time? To understand how he transformed the field, we may look at two books published at the beginning and at the end of the most creative phase of Parker's career (Kuiper, 1953; Priest, 1982). The chapter on solar activity by Kiepenheuer (1953) in the first book gives various kinds of data about different solar phenomena without any clue how to unify them. The chapter on solar MHD by Cowling (1953) summarized the basic principles of MHD and expressed the hope that in future they might be useful for studying the Sun. Apart from a discussion of a long-discarded model of sunspots due to Alfvén, the chapter presented almost no real applications to the Sun. However, when we look at Priest's book published in 1982 (Priest, 1982), we realize that the subject is already organized and connected essentially in the way we would do today. Solar physics had become a unified science in the intervening three decades during which Gene Parker formulated dynamo theory, gave the idea of magnetic buoyancy, developed the theory of coronal heating and predicted the solar wind. It will be difficult find another similar example in any branch of astrophysics of one individual striding over the field as a colossus like this. I show in Figure 5 a cartoon of how the various topics in the study of solar MHD are logically connected to each other through a chain of causes-andeffects. What is most amazing is that Parker almost single-handedly discovered virtually all the important links needed for interconnecting various aspects of solar activity, as should be clear from our discussion. A historical account of Parker's works on solar MHD essentially becomes a history of the field of solar MHD during its most crucial years of development!

The next two sections will be devoted to Parker's contributions in the MHD of the solar convection zone and the solar corona. Apart from establishing the interconnecting network sketched in Figure 5, Parker also explored several side lanes of solar physics to develop theoretical ideas to explain many other solar phenomena. Some of Parker's other important contributions to solar physics will be discussed in section 6 before we turn to his non-solar contributions in section 7.

It may be mentioned that, during the early years of Gene Parker's career, not much was known about stellar activity. During the last few decades, it has been realized that many solar-like stars have starspots much larger than sunspots, stellar flares much more powerful than solar flares and activity cycles similar to the Sun: see the review by Choudhuri (2017). It is now clear that Parker's works on the Sun have a much broader significance, providing us the framework for understanding many aspects of stellar activity.

Since the majority of Parker's papers (not all of them!) had been based on the macroscopic equations of MHD, we provide a quick recapitulation of these equations before we start a detailed discussion of Parker's works. What Parker could coax out of these simple-looking equations almost appears magical to us today. The basic idea of MHD is that the fluid velocity \mathbf{v} and the magnetic field \mathbf{B} act on each other. Since Parker mainly used Gaussian units in his publications, we now write down the MHD equations for \mathbf{v} and \mathbf{B} in Gaussian units. The time evolution equation of \mathbf{v} is

$$\frac{\partial \mathbf{v}}{\partial t} + (\mathbf{v} \cdot \nabla) \mathbf{v} = -\frac{1}{\rho} \nabla \left(p + \frac{B^2}{8\pi} \right) + \frac{(\mathbf{B} \cdot \nabla) \mathbf{B}}{4\pi\rho} + \mathbf{F}, \tag{1}$$

where ρ is the density, p is the pressure and \mathbf{F} is a body force per unit mass such as gravity: see, for example, Choudhuri (1998), sect. 14.1. When we leave out the magnetic terms, which arise from the Lorentz force, we are left with the well-known Euler equation of fluid mechanics. It is not difficult to explain the physical significance of the magnetic terms. The term $B^2/8\pi$, which appears with the gas pressure p inside the expression of a gradient force, is clearly of the nature of pressure. We call it *magnetic pressure*. The other magnetic force term involving $(\mathbf{B}.\nabla)\mathbf{B}$ would be zero when the magnetic field lines are straight. It arises only when the magnetic field lines are bent and tries to straighten them. It is called *magnetic tension*. To understand how \mathbf{v} acts on \mathbf{B} , we now have to look at the time evolution equation of the magnetic field,

which is known as the *induction equation*:

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B}) + \eta \nabla^2 \mathbf{B},\tag{2}$$

with

$$\eta = \frac{c^2}{4\pi\sigma},\tag{3}$$

where c is the speed of light and σ is the electrical conductivity: see, for example, Choudhuri (1998), sect. 14.1. Since $1/\sigma$ is the resistivity, the last term in (2) corresponds to the decay of the magnetic field due to the resistivity of the medium. The term $\nabla \times (\mathbf{v} \times \mathbf{B})$ can be shown to imply that the velocity field \mathbf{v} makes the magnetic field move with the plasma—an effect first discovered by Alfvén (1943) and often referred to as Alfvén's theorem of flux freezing.

4 MHD of the solar convection zone

The heat generated by nuclear fusion near the centre of the Sun is transported by convection from about $0.7R_{\odot}$ to R_{\odot} : see, for example, Choudhuri (2010), sects. 3.2.4 and 4.4. This region having the shape of a spherical shell is known as the convection zone and is found to be unstable to convection. Although we observe magnetic fields only on the solar surface and infer the nature of magnetic fields within the convection zone only on the basis of indirect arguments, reasonable theoretical considerations suggest that the plasma β , i.e. the ratio of the gas pressure to the magnetic pressure, is much larger than 1 within the convection zone except very near the surface. This is in contrast to the corona where the plasma β is less than 1 in many regions and the magnetic field controls the dynamics. Since the magnetic field does not control the dynamics of the convection zone, it may a priori appear that the role of the magnetic fields may not be so important there. In reality, however, the convection zone is of central interest to MHD as the region where the magnetic field originates.

As already mentioned in section 3, Parker wrote one seminal paper on how magnetic fields are produced by the dynamo process in the convection zone (Parker, 1955a) and another seminal paper on how these fields rise through the convection zone to reach the surface due to magnetic buoyancy (Parker, 1955b). Both these papers were submitted to *Astrophysical Journal* on October 18, 1954, indicating that Parker looked at these related problems from a unified viewpoint, although he eventually wrote two separate papers for two parts of the problem. The dynamo paper was revised on May 11, 1955, but no such revision date is given for the buoyancy paper, suggesting that it was probably accepted readily by the referee without requiring any revisions. The buoyancy paper (Parker, 1955b) appeared before the dynamo paper (Parker, 1955a). Curiously, Parker motivates the discussion of the buoyancy paper by summarizing some relevant results from the dynamo paper was yet to appear! I

may point out another perhaps irrelevant fact. Parker used SI units for electromagnetic quantities in these two early papers, although in later life he always used Gaussian units. By the time he wrote his solar wind paper three years later, he had already switched over to Gaussian units.

We shall now discuss the buoyancy paper (Parker, 1955b) before turning to the dynamo paper (Parker, 1955a) after that.

4.1 Magnetic buoyancy

Often one finds two sunspots side by side approximately at the same latitude. It was discovered by Hale et al (1919) that two sunspots in such a pair usually have opposite magnetic polarities. The aim of Parker (1955b) was to provide the first satisfactory theoretical explanation of this important observation. It was already known for nearly a century that the angular velocity at the solar surface varies with latitude, becoming a little bit weaker at higher latitudes. Although nothing was known in 1955 about the nature of differential rotation underneath the solar surface, the surface observations forced the conclusion that there had to be a variation of angular velocity in the interior. As a consequence of flux freezing, the differential rotation in the solar interior was expected to stretch out the magnetic field inside the Sun to produce a strong toroidal component (i.e. a component in the ϕ direction in spherical coordinates with respect to the Sun's rotation axis as the polar axis), unless magnetic field lines were lying exactly on the contours of constant angular velocity (Ferraro, 1937). If a part of the toroidal magnetic field produced due to the stretching by differential rotation becomes buoyant, Parker (1955b) realized that this part would rise to the surface to produce a bipolar sunspot pair, as sketched in Figure 6 taken from Parker's paper. Parker (1955b) gave a disarmingly simple argument for how a part of the toroidal field may become buoyant. Consider a region of strong toroidal field surrounded by gas without much magnetic field—a configuration which we may call a *flux tube*. Inside the flux tube, we would have magnetic pressure $B^2/8\pi$ in addition to the gas pressure p_i , which follows from (1). This total pressure has to be balanced by the external gas pressure p_e leading to the condition

$$p_e = p_i + \frac{B^2}{8\pi}.\tag{4}$$

It follows that $p_i < p_e$, which may often imply that the internal density of the flux tube would be less than the external density. If this is the case, then that part of the flux tube with lower density would be buoyant and rise against the gravitational field of the Sun to reach the surface where it produces the bipolar sunspot pair.

In order to produce a bipolar sunspot pair, only a part of the toroidal magnetic field should rise and the two ends of this part should remain 'clamped'. Parker (1955b) did not present much discussion of any possible clamping mechanism in the original paper on magnetic buoyancy, except to mention that

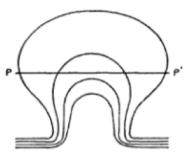


Fig. 6 A sketch from the magnetic buoyancy paper (Parker, 1955b) showing how a part of the magnetic field has risen to produce a bipolar sunspot pair at the solar surface. Reproduced by permission of the AAS.

the length L of the toroidal flux tube should be sufficiently large to ensure that magnetic tension would not be too strong to oppose magnetic buoyancy. Parker revisited the problem of magnetic buoyancy two decades later (Parker, 1975), when he presented a more detailed analysis which provided a clue for the clamping mechanism. Parker (1975) showed that magnetic buoyancy gets reinforced within the solar convection zone where the temperature gradient is slightly stronger than the adiabatic gradient, but the magnetic buoyancy would be suppressed in the regions of subadiabatic temperature gradient below the bottom of the convection zone. Suppose we have a toroidal flux tube slightly below the bottom of the solar convection zone, of which a part has come within the convection zone by some means. Then that part would become buoyant, whereas buoyancy would be suppressed in other parts which remain anchored. This theoretical idea readily suggests the possibility of numerical simulations. From the full equations of MHD, Spruit (1981) derived an equation for the dynamics of a 'thin' flux tube, of which the radius of cross-section is much smaller than various scale heights. Moreno-Insertis (1986) carried out the first simulation of the buoyant rise of a magnetic flux tube always lying in a vertical plane.

Hale's collaborator Joy had noted that sunspot pairs did not appear at exactly the same latitude, but usually had a small tilt with the sunspot in the forward direction (with respect to the rotation axis) lying slightly closer to the equator, and this small tilt was found to become larger at higher latitudes (Hale et al, 1919). The existence this tilt in bipolar sunspot pairs and its increase with latitude is nowadays referred to as *Joy's law*. One important question was whether this tilt could arise from the effect of the Coriolis force due to the Sun's rotation acting on the rising flux tubes. We (Choudhuri, 1989; D'Silva and Choudhuri, 1993) carried out the first 3D simulations of the rise of flux tubes in a spherical geometry with the Coriolis force included. We found that the results of simulations matched the observational data of Joy's law only if the magnetic field at the bottom of the convection zone had a strength of about 10^5 G (D'Silva and Choudhuri, 1993). This result was soon confirmed by independent simulations of other groups (Fan et al, 1993;

Caligari et al, 1995). This provided the first tight constraint on the value of the toroidal magnetic field at the bottom of the convection zone and played a vital role in the development of the solar dynamo theory, as we shall point out in subsection 4.2.

Within the last few years, increased powers of computers have enabled a few groups to go beyond the thin flux tube equation assumption and model the buoyant rise of flux tubes using the full MHD equations. Instead of entering a discussion of this subject, we refer the readers to the excellent review by Fan (2021).

4.2 Solar dynamo

A key issue in astrophysical MHD is to understand how magnetic fields arise in astrophysical systems. Is it possible to have some flows in electrically conducting fluids which would sustain a magnetic field? This became the central question of what has come to be known as *dynamo theory*. The early history of this field has been summarized by Moffatt (1978), Chapter 1.

The first important landmark in dynamo theory was a negative theorem due to Cowling (1933), who showed that an axisymmetric flow cannot sustain an axisymmetric magnetic field. It was conjectured by some that *Cowling's* theorem may be a special case of a more general theorem that fluid flows cannot sustain magnetic fields against Ohmic decay. If that were the case, then dynamo theory would have no solution within the framework of MHD. It is rumoured that even Einstein held this view (Krause, 1993). Those who still tried to solve the dynamo problem knew that they had to incorporate non-axisymmetric flows (Elsasser, 1946).

If convection takes place in an astrophysical body which is undergoing rotation, then the convective motions are affected by the Coriolis force and become helical in nature. It was the great insight of Parker (1955a) to realize that such helical convective motions can sustain magnetic fields, provided certain conditions are satisfied. Since these helical convective motions are turbulent, they are certainly not axisymmetric and one easily avoids Cowling's theorem. Parker (1955a) developed a mean field theory of averaging over turbulence and arrived at the famous *dynamo equation*, the central equation in the theory of turbulent dynamos. The modelling of all astrophysical dynamos since then has been based on the fundamental ideas developed by Parker in this seminal paper (Parker, 1955a). For a pedagogical discussion of turbulent dynamo theory and its application to the Sun, the readers are referred to Choudhuri (2015).

Parker (1955a) himself solved the dynamo equation in a situation appropriate for the Sun and obtained a wave-like solution. Observationally, it is found that sunspots appear at lower and lower latitudes with the progress of the solar cycle. This was interpreted as a dynamo wave propagating equatorward and Parker's dynamo wave solution was proposed an an explanation of the solar cycle. It was a characteristic of Parker's way of thinking that he always wanted to have a physical understanding of any unusual result which he derived mathematically. After presenting the dynamo wave solution, Parker (1955a) gave a

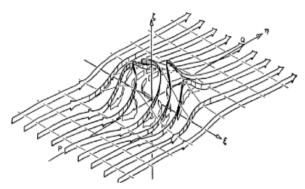


Fig. 7 A figure from the dynamo paper (Parker, 1955a) showing a few toroidal magnetic field lines to explain how the poloidal field is produced and how the dynamo wave for modelling the solar cycle arises. Reproduced by permission of the AAS.

physical explanation of how this solution arises. This physical explanation is simply vintage Gene Parker. Anybody who wishes to have an understanding of Gene Parker's unique way of thinking about physics must read this physical explanation of the dynamo wave in his own words, which was reproduced more clearly in Parker (1979a), pp. 632–633.

Parker's dynamo paper (Parker, 1955a), by far the most influential paper in the history of this subject, had three remarkable achievements.

- 1. The feasibility of dynamo action within the framework of MHD was demonstrated for the first time.
- 2. It was shown—probably for the first time—that turbulence, which we normally expect to produce disorder, can give rise to coherent structures like the large-scale magnetic field. The study of how coherent structures emerge out of turbulence due to an *inverse cascade* later became an important field of research.
- 3. An attractive model of the solar cycle was proposed for the first time.

Several of Parker's classic papers—notably the solar wind paper (Parker, 1958)—provide immensely pleasurable reading. However, the original dynamo paper was not an easy read. Going through that paper, one feels that Parker (1955a) was struggling to put forth several difficult concepts which were completely unfamiliar to the majority of astrophysicists in that era. Probably very few people read or understood the paper when it was published. According to Web of Science, the paper received only 15 independent citations during the decade 1956–65!

After Steenbeck et al (1966) developed a more systematic procedure for averaging over turbulence in the dynamo problem, the subject became more accessible. They used the symbol α for the coefficient which captures the essence of helical turbulent motions (Parker had used the symbol Γ). As a result, the effect of helical turbulence twisting a magnetic field came to be known as the α -effect. Parker (1955a) had earlier constructed a model for

the solar dynamo by solving the dynamo equation in a rectangular geometry without boundaries. Steenbeck and Krause (1969) constructed more realistic models of the solar dynamo by solving the dynamo equation in a spherical geometry appropriate for the Sun. Apart from the α -effect, the differential rotation of the Sun indicated by $\Omega(r, \theta)$ is the other crucial quantity responsible for dynamo action. That is why this type of dynamo models came to be known as the $\alpha\Omega$ dynamo models. The necessary condition to make the dynamo wave propagate equatorward in agreement with observational data was found to be

$$\alpha \frac{\partial \Omega}{\partial r} < 0 \tag{5}$$

in the northern hemisphere. This condition is often referred to as the *Parker-Yoshimura sign rule*—after Parker (1955a) who obtained a primitive version of this condition from his calculations in rectangular geometry and after Yoshimura (1975) who generalized the condition by considering a spherical geometry. In the 1970s and 1980s when not much was known about the differential rotation of the Sun below its surface, different groups constructed models of the solar dynamo by specifying α and $\Omega(r, \theta)$ in such a manner that the condition (5) was satisfied.

Although the $\alpha\Omega$ model of the solar dynamo appeared reasonable and attractive, some limitations of this model became apparent in the 1980s. When *helioseismology*—the study of solar oscillations—succeeded in mapping the differential rotation in the interior of the Sun, it turned out to be very different from what used to be assumed in the early $\alpha\Omega$ dynamo models. Another serious difficulty arose when simulations of magnetic buoyancy suggested that the toroidal magnetic field inside the Sun must be as strong as 10⁵ G, as pointed out in subsection 4.1. The α -effect involves the twisting of the magnetic field has to be weaker than about 10⁴ G. The magnetic field strength of 10⁵ G suggested that the α -effect would be suppressed inside the Sun. The older $\alpha\Omega$ dynamo models had to be modified and amended in important ways. Parker himself became aware of some of these difficulties and proposed in a later paper (Parker, 1993) that one way of circumventing them may be to develop a model in which the differential rotation and the α -effect operate in different layers.

An alternative to the α -effect was suggested quite early by Babcock (1961) and Leighton (1969). In the Babcock-Leighton mechanism, the decay of tilted bipolar sunspots gives rise to magnetic fields similar to what one would get from the α -effect. It was realized in the 1970s and 1980s that there was a fluid flow at and underneath the solar surface known as meridional circulation. In a new type of dynamo model developed in the 1990s, known as the flux transport dynamo model, it was found that the Babcock-Leighton mechanism, when combined with meridional circulation, produced particularly good fits to various aspects of the solar cycle (Wang et al, 1991; Choudhuri et al, 1995; Durney, 1995). This model has become increasingly popular—especially after a prediction for the following cycle based on this model (Choudhuri et al, 2007)

turned out to be correct. Readers desirous of learning more about the recent developments in solar dynamo and about the flux transport dynamo model may turn to the review articles by Charbonneau (2010, 2014) and Choudhuri (2011, 2014, 2023).

The $\alpha\Omega$ dynamo model proposed by Parker (1955b) was undoubtedly the most important single step in our theoretical understanding of the solar dynamo, even though we now believe that the original model has to be modified in significant ways. Although the α -effect may be suppressed in the regions inside the Sun where a strong toroidal magnetic field is produced by differential rotation, there is no doubt that this is a real effect operative in many astrophysical systems and has been supported by numerical simulations. There have been many impressive simulations of the geodynamo starting from the work of Glatzmaier and Roberts (1995). These simulations show the α -effect at work—exactly the way Parker envisaged it many decades ago.

5 MHD of the outer solar atmosphere

Parker wrote more papers on the solar corona (if we include his solar wind papers also in this category) than on any other astrophysical topic throughout his career. Certainly the solar corona provides illustrations of many processes important in plasma astrophysics. Since the emission from the corona is much feebler than the emission from the solar surface, the corona is not visible from the Earth's surface under normal circumstances and has been studied historically during total solar eclipses. In the 1930s, Lyot (1939) developed the coronagraph which produces an artificial eclipse inside the telescope by blocking light from the solar disk. However, diffuse light still makes it very difficult to see the corona and a coronagraph has to be taken to a high mountain to get a glimpse of the corona. From the 1970s, it has been possible to observe the solar corona continuously with the help of coronagraphs carried in space missions. Because of the high temperature, the corona emits copious amounts of X-rays. X-ray imaging instruments sent to space (starting from Skylab in the early 1970s) have provided increasingly striking images of the X-ray emitting regions of the corona. X-ray emissions detected from many solar-like stars indicate that they also have similar stellar coronae.

Even a visual inspection of the structures in the solar corona suggests that magnetic fields must be behind them. After the development of the idea of magnetic buoyancy (Parker, 1955b), it became clear that the magnetic fields created within the solar convection zone would come out in the corona. Although a direct measurement of the magnetic fields in the corona has proved particularly challenging, solar astronomers started gathering different kinds of evidence within the last few decades that the corona is full of magnetic fields. We have already pointed out in the beginning of section 4 that the plasma- β is expected to be less than 1 in many regions of the lower solar corona, indicating that magnetic fields would control the dynamics in those regions. Parker's important contributions to coronal physics can be broadly classified under three topics: (i) the basic theory of magnetic reconnection; (ii) the theory of coronal heating and (iii) the theory of solar wind. If we wanted to present our discussion of these topics in a chronological order depending on the time when Parker worked on these topics, then we have to put topic (ii) after topic (iii), since Parker worked extensively on some of the theoretical aspects of the coronal heating problem in the last few years of his active scientific career. However, we have decided to follow an order which appears more logical to us. After all, it is the hot corona which drives the solar wind.

5.1 Solar flares and magnetic reconnection

The importance of magnetic fields in the dynamics of the solar corona first became apparent from the study of solar flares, which are gigantic explosions taking place above the solar surface. A powerful flare may release energy of order 10^{32} erg within a time of the order of an hour. The crucial issue was to identify this source of energy. The first recorded flare observed by Carrington (1859) occurred over a sunspot. Further observations over the next few decades established that flares take place above solar active regions, which are expected to be dominated by magnetic fields ever since the discovery of magnetic fields in sunspots (Hale, 1908). It was natural to guess that the magnetic energy would be the source of the energy released during a solar flare. The important question was to work out the detailed physics of the mechanism by which this energy conversion takes place.

It is clear from (2) that the term $\eta \nabla^2 \mathbf{B}$ corresponds to the magnetic field (i.e. the magnetic energy) getting dissipated due to the resistivity. In coronal plasma with very low resistivity, this term can be significant only if $\nabla^2 \mathbf{B}$ is large. After Dungey (1953) pointed out the importance of magnetic neutral points, Sweet (1958) realized that $\nabla^2 \mathbf{B}$ would be large if we have a null surface with oppositely directed magnetic fields on the two sides. Since Ampére's law suggests that the current density would be very high at the null surface. such surfaces are often referred to as *current sheets*. What is more, if the magnetic field at the current sheet is dissipated without any motions within the plasma, then that would cause a decrease in the magnetic pressure, leading to a pressure imbalance. This suggests that plasma with oppositely directed magnetic fields on the two sides of the neutral surface (or the current sheet) would flow into the region of the neutral surface. As a result of this, the process can continue as long as we have fresh magnetic fields brought from the two sides by the inflowing plasma. Based on Sweet's ideas, Parker (1957) managed to estimate the velocity with which the inflowing plasma would move towards the current sheet. This inflowing velocity is known as the Sweet-Parker reconnenction rate. Since the plasma which is squeezed out of the region of the neutral surface contains magnetic field lines, parts of which were originally on the two opposite sides of the neutral sheet, this process came to be known as magnetic reconnection. It may be worthwhile to point out a little bit of the interesting publication history. Sweet presented his work at the International

Astronomical Union Symposium 6 held in Stockholm during 27–31 August, 1956. Sweet's paper came out in the Proceedings of Symposium, which was eventually published only in 1958 (Sweet, 1958). Due to this delay in the publication of Sweet's paper, Parker's paper appeared in print earlier (Parker, 1957). However, Parker (1957) generously titled the paper "Sweet's mechanism for merging magnetic fields in conducting fluids" and pointed out in the opening sentence that he was elaborating on Sweet's ideas.

Soon after the idea of magnetic reconnection was put forth, it was realized that this is an extremely important process in many plasma systems in the laboratory and in many astrophysical systems. However, the Sweet-Parker reconnection rate seemed inadequate to explain the rather short rise-phase and duration of solar flares. The reconnection has to proceed at a much faster rate for release of such a substantial amount of energy in such a short time during a typical solar flare. With this realization, the search for reconnection at a faster rate began. One of the first influential scenarios for faster reconnections was proposed by Petschek (1964). As numerical simulations of reconnection started, it was apparent that the reconnection rate may depend on boundary conditions far away—making this a particularly challenging problem, which depended not only on the local conditions, but also on what was happening far away. Readers desirous of learning more about this complex subject are referred to the monographs by Priest and Forbes (2000) and Priest (2014) and the living review article by Pontin and Priest (2022). For a discussion of the physics behind solar flares, see Shibata and Magara (2011) and Priest (2014). We shall now turn our attention to another subject in which magnetic reconnection plays a crucial role.

5.2 Coronal heating

While the temperature of the solar surface is about 5800 K, the temperature in certain regions of the corona can be as high as $(1-2) \times 10^6$ K. It was first realized in the 1940s that the corona is much hotter than the solar surface. Some emission lines seen in the solar corona were identified by Edlén (1943) as lines produced by iron atoms which have lost several electrons. Such a loss of several electrons from iron atoms would be possible only if the corona had a very high temperature. What produces the high temperature of the corona became a central question of theoretical solar physics. Biermann (1948) and Schwarzschild (1948) were the first to suggest that acoustic waves produced by convective motions just below the solar surface could propagate to the corona and dissipate there to produce the high temperature, whereas Alfvén (1947) proposed that MHD waves do this job. As the magnetic nature of the corona became more apparent, it was realized that we need to consider MHD waves propagating in the corona rather than simple acoustic waves. In order to produce the high temperature of the corona, the MHD waves have to dissipate in the corona rather than passing through it without much dissipation, which would be the case if the resistivity of the corona was too low (as expected). Mechanisms such as *phase mixing* and *resonant absorption* have been suggested

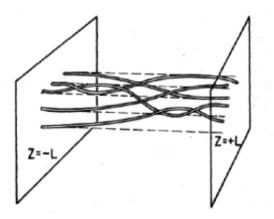


Fig. 8 A famous figure from the coronal heating paper (Parker, 1972) showing how magnetic field lines between two parallel planes develop a complex topology due to the motions of footpoints. Reproduced by permission of the AAS.

to enhance the dissipation. We shall not enter into a detailed discussion of this vast subject. Interested readers are referred to a brief discussion in Priest (2014), pp. 356–364.

Parker (1972) suggested an alternative mechanism of how the heat is produced in the corona. It is expected that magnetic buoyancy would make the magnetic field rise through the convection zone to come out in the corona in the form of magnetic loops. When X-ray images of the corona from space missions first became available in the 1970s, it was indeed found that the corona is full of X-ray emitting loops. The enhanced emission from these loops suggested that the magnetic loops are the hottest regions of the corona and that these loops are the primary locations in the corona within which the heat is produced. One may naively expect that the magnetic fields inside coronal magnetic loops would be in magnetostatic equilibrium. However, these loops are not isolated systems. Magnetic field lines in these loops must continue below the photospheric surface of the Sun. The convective motions present there are expected to move the magnetic footpoints of the loops, thereby disturbing the equilibrium of the the overlying magnetic structures. As a result, the magnetic fields in the loops would try to relax to new configurations satisfying magnetostatic equilibrium. On the basis of a very short mathematical derivation, Parker (1972) argued that the magnetic fields would relax to configurations having discontinuities in the magnetic field, i.e. would give rise to current sheets where magnetic reconnection can take place to produce the heat.

Parker often told many of us that the 1972 paper on coronal heating was his own favourite among all his papers. This certainly turned out to be his most controversial paper. Many peers in the community were not sure whether the argument Parker (1972) gave on the basis of a short derivation was sufficiently sound. It is worthwhile to reproduce the short derivation here. Parker (1972) realized that the curvature of the coronal loop was not essential in this problem. So he considered a uniform initial magnetic field in one direction (say the z

direction) between two perpendicular plane surfaces (representing the two ends of the loop at the photospheric surface). Now suppose that random motions on the plane surfaces perturb the magnetic field, as sketched in Figure 8. The perturbed magnetic field would try to relax to a configuration satisfying the magnetostatic equilibrium equation, which we arrive at by putting $\mathbf{v} = 0$ in (1) and is

$$-\frac{1}{\rho}\nabla\left(p+\frac{B^2}{8\pi}\right) + \frac{(\mathbf{B}.\nabla)\mathbf{B}}{4\pi\rho} = 0.$$
 (6)

We now write the magnetic field as

$$\mathbf{B} = B_0 \mathbf{e}_z + \mathbf{b},\tag{7}$$

where $B_0 \mathbf{e}_z$ is the initial magnetic field assumed uniform and **b** is the perturbation produced in it by footpoint motions. On substituting (7) in (6) and keeping only terms linear in **b**, we obtain

$$-\frac{1}{\rho}\nabla\left(p+\frac{B_0b_z}{4\pi}\right) + \frac{B_0}{4\pi\rho}\frac{\partial\mathbf{b}}{\partial z} = 0.$$
(8)

On taking the divergence of this equation and keeping in mind that $\nabla \mathbf{.b} = 0$, we arrive at

$$\nabla^2 \left(p + \frac{B_0 b_z}{4\pi} \right) = 0, \tag{9}$$

which is the Laplace equation, one of the most thoroughly studied equations of mathematical physics. If we demand that the solution of this equation must not blow up anywhere (including infinity), then the only possibility is that the solution is spatially constant. We expect (9) to hold between the two parallel plates where we rule out the possibility of the solution blowing up anywhere. This forces us to the conclusion

$$p + \frac{B_0 b_z}{4\pi} = \text{constant.}$$

It then follows from (8) that

$$\frac{\partial \mathbf{b}}{\partial z} = 0. \tag{10}$$

This implies that magnetostatic equilibrium requires an invariance along a symmetry direction.

We expect everybody to agree with this derivation so far. The uncertainly arises when we try to interpret (10). If we consider the idealized case of a plasma with zero resistivity, then the only term on the right hand side of (2) is $\nabla \times (\mathbf{v} \times \mathbf{B})$, which would imply that the magnetic field would move with the plasma and magnetic topologies cannot change. In general, we expect the topology of the magnetic field lines resulting from arbitrary footpoint motions to be such that it may not be possible to satisfy (10). In other words, we seem to have two requirements which are difficult to reconcile. On the one hand, the magnetostic equilibrium demands that (10) be satisfied. On the other hand, topological constraints may make it impossible to satisfy (10). What then happens? Parker (1972) argued that the magnetic field would relax to a configuration with internal discontinuities where the magnetic field would cease to be continuous and differentiable. In other words, many current sheets may arise. Magnetic reconnection would take place at these current sheets and heat is expected to be generated to cause the high temperature of the corona.

Do we find this argument convincing? It is no wonder that many in the scientific community felt somewhat unsure about this argument. A review article on coronal heating mechanisms published in 1981 (Kuperus et al. 1981) did not even cite Parker's 1972 paper! A great deal of interest was again rekindled in this subject from the early 1980s when the space-based Einstein X-ray Observatory established that many solar-like stars have coronae emitting X-rays (Pallavicini et al, 1981). Based on some reasonable assumptions, Parker (1983) estimated the amount of energy expected to be generated due to the formation of magnetic discontinuities in the solar corona and found that it approximately matches the energy budget needed to heat the corona. Parker (1988) also argued that the magnetic discontinuities would give rise to many small reconnection regions, which he called *nanoflares*, rather than one large reconnection region as in a large flare. Since the dissipation of MHD waves in the corona had been proposed as another mechanism for coronal heating, a debate took place in the 1980s and 1990s as to which of the two mechanisms—dissipation of MHD waves and current sheet formation due to footpoint motions—was the correct mechanism for coronal heating. A view has emerged gradually over the years that both these mechanism must be at work in different regions of the corona. Current sheet formation is possible only in regions of closed magnetic field, such as coronal loops. They are also the hottest regions of the corona, suggesting that a different heating mechanism may be at work inside them. Presumably the coronal loops are heated by the formation of many small current sheets as envisaged by Parker, whereas the other regions of the corona with open magnetic field lines are probably heated by the dissipation of MHD waves.

Apart from applying his theory to several aspects of observational data, Parker was concerned with the question whether one could justify the arguments of his 1972 paper by more rigorous detailed calculations. A heated debate took place on this subject in the mid-1980s within the American solar physics community when van Ballegooijen (1986) claimed that the invariance condition (10) may not be essential for magnetostatic equilibrium. However, his analysis pointed out that the braiding of field lines by footpoint motions may lead to a cascade of energy to smaller length scales, as envisaged by Parker. Parker himself wrote a series of papers in the late 1980s and the early 1990s advancing various kinds of arguments to justify the suggestions he made in his 1972 paper. For example, he pointed out that the mathematical theory of the structure of field lines would be analogous to the mathematical theory of light

rays in a medium of varying refractive index (Parker, 1989). Parker exploited this analogy to draw various conclusions.

Perhaps Parker had not struggled with any other scientific question as much as he struggled in the later part of his scientific career to understand the mathematical structure of the theory of magnetostatic equilibria and to address the question whether the theory inevitably leads to the conclusion that magnetic discontinuities must arise in the general situation. It is a difficult subject and it has to be admitted that Parker did not attract many followers. In other words, there were not many in the scientific community to take the lead from Parker's work to carry on further investigation of this subject. As a result, the majority of Parker's many papers dealing with these basic theoretical issues written after mid-1980s received relatively few citations, although some of the papers in which he discussed the application of his theoretical ideas to explain the observations of solar and stellar coronae became citation classics (Parker, 1988)! When Parker eventually felt that he had succeeded in developing a unique perspective of the subject, he decided to put forth a coherent account of the subject in his monograph Spontaneous Current Sheets in Magnetic Fields (Parker, 1994). It is certainly not an easy book to read—in contrast to Parker's earlier monograph Cosmical Magnetic Fields (Parker, 1979a), known for its remarkable lucidity, which is a pleasure to read because of its elegant writing style. Arguably, Parker had to deal with an intrinsically difficult subject in his later monograph. We do know of a few examples of scientific investigation which did not get much attention from the contemporaries, but led to important developments many years after the work. Still, when the sustained efforts of a great scientist over many years do not get too much attention from contemporaries, one cannot avoid asking an awkward question. Were the scientific returns commensurate with the time and energy Parker spent on this subject? I would humbly submit that my own understanding of this complicated subject is very limited and I am not qualified to answer this question. I refer the readers to a review by Low (2023), who delivered the prestigious Crafoord Prize lecture on behalf of the ailing Parker (who won this Prize in 2020) and had many discussions on the magnetostatic theorem with Parker in his declining years.

5.3 Solar wind

We now come to Parker's most famous work: the prediction of the solar wind. At a time when the solar corona was known to be very hot but there was not much understanding about the reason behind this, Parker (1958) pointed out that a hot corona would drive an outward flow of plasma through the solar system. There has never been a more radical transformation in our view of the space environment of our planet Earth. The prevalent view for several centuries was that the interplanetary space is essentially empty, through which the planets encircle the Sun. Parker's work suggested that the Earth is basically embedded in the extended atmosphere of the Sun, leading to the possibility

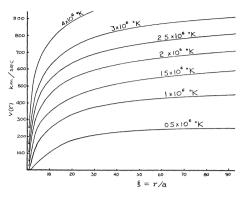


Fig. 9 A figure from the solar wind paper (Parker, 1958) showing how the speed of the solar wind was found to vary with radial distance from the Sun on the basis of the theoretical model for different assumed values of the temperature. Reproduced by permission of the AAS.

of understanding how phenomena on the Sun (like solar flares) may affect the Earth.

To explain why comet tails turn away from the Sun, Biermann (1951) suggested that there may be a corpuscular outflow from the Sun which turns the comet tails in the outward direction with respect to the Sun. On the other hand, Chapman (1957) pointed out that the high temperature of the corona suggested that the corona would extend to a very large distance from the Sun. Now, it is not possible for a stream of plasma to flow through a background of plasma at rest. That would lead to two-stream instability. Parker realized that the outer parts of Chapman's extended corona must expand to produce Biermann's corpuscular outflow. From the basic equations, Parker (1958) was able to find a solution which exactly corresponded to this situation. Parker's original calculation was essentially hydrodynamic, although in the later part of the paper he discussed how the wind would affect the magnetic field coming out of the Sun. In fact, the calculations are so straightforward that a perusal of Parker's paper may give the misleading impression that this work could be done by an average scientist of much lesser abilities. However, only Parker had the great insight to look at this problem in this particular way.

Assuming spherical symmetry, if the radially outward velocity is v at a radial distance r where the density is ρ , mass conservation suggests that

$$\rho v r^2 = \text{constant.}$$
 (11)

To consider a static hydrodynamic flow, we need to use the radial component of (1) by putting the time derivative term and the magnetic force terms to zero. This gives

$$\rho v \frac{dv}{dr} = -\frac{dp}{dr} - \frac{GM_{\odot}}{r^2}\rho, \qquad (12)$$

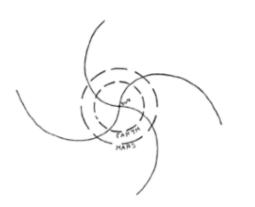


Fig. 10 A sketch from the solar wind paper paper (Parker, 1958) showing how the magnetic field lines of the rotating Sun would get stretched due to the outflowing solar wind, giving rise to what are now called Parker spirals. Reproduced by permission of the AAS.

where we have put the appropriate expression for the Sun's gravitational field in the force term. It is clear that the two scalar equations (11) and (12) involve three independent variables—namely ρ , p and v— which would all be functions of r alone in a spherically symmetric situation. If one can relate ρ and p, then the number of independent variables would be equal to number of equations, which can then be easily solved. Parker (1958) made the simplest assumption of an isothermal condition. On solving (11) and (12), he was able to find solutions involving flows which start from very low subsonic velocities near the solar surface and eventually become supersonic at some distance away from the Sun. Figure 9 shows some solutions obtained by Parker for the variation of velocity v with the radial distance r for different assumed values of the temperature of the corona. While the solar wind is expected to stretch out any magnetic field lines coming out of the Sun, Parker (1958) realized that the solar rotation would impart a spiral structure to the field lines in the equatorial plane of the Sun, as shown in Figure 10. These spirals are now referred to as *Parker spirals*. Whether a solar explosion would affect the Earth often crucially depends on whether the site of the explosion and the Earth lie close to one Parker spiral. Parker (1958) estimated that the mass loss of the Sun during its lifetime due to the solar wind would be negligible. However, the magnetic field stretching out of the Sun would be an efficient transporter of angular momentum and the Sun might have lost a significant amount of angular momentum taken away by the solar wind, implying that the Sun might be rotating faster when it was young. The basics of solar wind theory are discussed so beautifully and coherently in Parker's original paper that it can still be recommended as a pedagogical introduction to students who want to learn the subject!

Parker became interested in this subject during a visit of Biermann to Chicago and then had a discussion with Chapman when he visited the High Altitude Observatory in Boulder where Chapman was working. Parker has given an account of the dramatic history behind the discovery of the solar wind in a *Scientific American* article (Parker, 1964). It is well known that the solar wind paper was rejected by two referees. Here is Parker's own account of the publication history (Parker, 2014) (SCR refers to solar corpuscular radiation):

I wrote it up for publication in The Astrophysical Journal, of which, fortunately, Prof. Chandrasekhar was editor at that time. The referee's report came back in a few months with the suggestion that the author should spend some time in the library to familiarize himself with the SCR before attempting to write a scientific paper on the subject. There was no specific criticism of the mathematics or of the interpretation of the observations. So Chandra sent the paper to a second "eminent" referee, with essentially the same result. I emphasized to Chandra that these two referees, for all their hostility, could find no scientific error. Then one day Chandra came to my office and said, "Now see here, Parker, do you really want to publish this paper? I have sent it to two eminent referees, and they both say the paper is wrong." I replied that the referees had no scientific criticism. He thought for a moment and then said, "Alright, I will publish it." Some years later he told me that he had been skeptical about the paper, but without objective criticism, he felt obliged to publish it. To my regret I failed to save the two referee reports ...

Chandrasekhar agreed to publish the paper in spite of his own reservations. However, Joseph Chamberlain, another colleague of Parker working at the Yerkes Observatory belonging to the University of Chicago, was convinced that Parker's theory could not be correct and wrote a paper pointing out why he considered it wrong (Chamberlain, 1960). Figure 11 shows a part of Parker's letter commenting on the solar wind soon after he had developed its theory. Parker's generous nature is rather evident in this letter. Instead of bragging about his own work, he gives a lot of credit to Biermann.

The theory of the solar wind was generally accepted only after in-situ measurements from space vehicles confirmed its existence. It is a remarkable historical coincidence that Parker's theory of the solar wind was worked out almost exactly at the time when the first artificial satellite Sputnik was launched (on 4 October 1957), heralding a space race between the USSR and USA. The first detection of the solar wind was made by the Russian spacecraft Luna-2 (Gringauz et al, 1960). It may be kept in mind that this was the era of the infamous cold war which reached its peak during the Cuban missile crisis of 1962. It is quite remarkable that Russian space missions were busy confirming the theory of an American scientist during the height of the cold war. What better example can one give of international co-operation in science! An interesting Russian perspective of the history of the solar wind can be found in Obridko and Vaisberg (2017).

After the existence of the solar wind was established, Parker (1963a) wrote a monograph on the subject. He also pointed out the possibility of similar winds in other stars and discussed the extension of the theory when one goes beyond the isothermal assumption in a comprehensive review of the subject (Parker, 1965a). After this review presenting his final point of view, he almost left the subject of solar wind theory and did not work on this subject much after that. The only aspect of the solar wind on which he worked extensively beyond the mid-1960s was the propagation of cosmic rays through the solar wind to be

And the collection of my I have to go to the University of Rochester Friday to give a talk on what I call the solar wind. Biermann observed some years ago that gas streams a tward in all directions from the sun with relocities of 500-1500 km/sec, and densities of the order of 102-103 hydrogen atoms/cm3 at the orbit of Earth. Nobody has taken Biemann's observations very seriously. If turns out, however, that on the basis of Biermann's observation, viz the solar wind, one expects the inner solar disordered magnetic field (~2x10-5 gauss) which extends from about the orbit Earth to the orbit of Jupiter. It also follows that the cosmic ray intensity should be low when the Solar wind is high with no particles below I Bev. And that the cosmic-ray intensity should sometimes drop by 10-2090 in a few hours. All of these are observed to happen, and to the same degree as the solar wind predicts. I have to talk about the same sluff at the National Academy of Sciences Symposium on plasma dynamics at Woods Hole in June

Fig. 11 A part of Parker's letter to his parents describing the solar wind. This letter is dated 16 February 1958, which means that it was written only a few weeks after the famous paper on solar wind was submitted to *The Astrophysical Journal* (on 2 January 1958). Credit: Eric Parker and Susan Kane-Parker.

discussed in subsection 6.1. This contrasts strikingly with Parker's engagement with the coronal heating problem till the end of his active research career. Perhaps he felt that some of the fundamental questions connected with the coronal heating problem had not been answered satisfactorily and he wanted to develop a deeper understanding of the subject. On the other hand, while many important research questions kept coming up in the field of solar wind, probably Parker felt that there were no such major unsettled conceptual issues in that field and he left the field which he single-handedly established for others to take forward.

I shall not try to present a comprehensive account of the later developments in solar wind theory, for which I refer the reader to Priest (2014), Chap. 13. Here I shall only make a few comments on the works which extended Parker's original work. Parker (1958) considered the effect of the solar wind on solar magnetic fields, but did not develop a full MHD theory combining the gas

and the magnetic field. This was done by Weber and Davis (1967) for the equatorial plane and was extended by Sakurai (1985) beyond this plane. One consequence of an MHD wind pointed out by Parker (1958) is the magnetic braking of rotation, as we have mentioned. The importance of such braking of rotation for different kinds of stars was recognized soon after Parker's work on the solar wind (Schatzman, 1962; Mestel, 1968). It has been realized from total solar eclipse photographs that closed magnetic regions in the corona often give rise to helmet-like structures, with the solar wind flowing by their sides. Such structures were modelled by Pneuman and Kopp (1971). As more and more X-ray images of the corona started coming from space missions, it became clear that the corona is anything but spherical, pointing out the need to go beyond the spherically symmetric model of the solar wind developed by Parker. X-ray images indicated the existence of dark coronal holes and the solar wind emanating from such holes was found to be more energetic. It became clear that some energy must be getting deposited in coronal holes in the right manner to produce a more efficient acceleration of the solar wind in those regions. This subject has been reviewed by Leer et al (1982). Let us end this discussion by pointing out that the Parker Solar Probe, named in honour of Parker and launched while he was still alive, is now exploring the regions of the corona from which the solar wind emanates. See Raouafi et al (2023) for a discussion of the science results obtained by this mission.

6 Other significant solar physics works

After summarizing some of Parker's most famous works on solar physics, I shall now briefly discuss some of his other important works in the field.

6.1 Theory of cosmic ray propagation

It was in the 1960s that Parker made fundamental contributions in the theory of the propagation of cosmic rays through the solar wind. By that time, the existence of the solar wind had been firmly established and it was realized that cosmic ray particles have to make their way through the solar wind to reach the Earth. All the other solar physics works of Parker which we summarize were based on the macroscopic MHD equations (1) and (2)—except his work on cosmic rays, for which he followed a more microscopic approach as we shall discuss now. Since my own knowledge of this subject is very limited, I shall restrict myself only to a few broad remarks and refer the interested reader to Jokipii (1971) for a rigorous review of how the field of cosmic ray propagation developed in the 1960s.

Cosmic rays were discovered by Hess (1912). By the middle of the twentieth century, there were enough indications that the cosmic ray flux reaching the Earth was affected by solar activity. Forbush (1954) discovered that there is a dip in the cosmic ray flux after a major solar flare. With more data of the cosmic ray flux gathered over the years, there was also the indication of an anti-correlation with the solar cycle—the cosmic ray flux decreasing at the time of

the sunspot maximum. It was clear that enhanced magnetic activity within the solar system made it more difficult for cosmic ray particles to reach the Earth. The important scientific question was to provide a proper theoretical framework to understand this.

To explain how the charged particles making up cosmic rays get accelerated to very high energies, Fermi (1949) proposed a famous mechanism involving interstellar gas clouds with magnetic fields which act as magnetic mirrors and reflect the gyrocentres of moving charged particles. According to the original theory of Fermi (1949), the charged particles are accelerated by repeated reflections from randomly moving interstellar gas clouds. While Fermi's idea of charged particles getting reflected from magnetic irregularities turned out to be very influential, it was realized by the late 1970s that blast waves emanating from supernova explosions provide more efficient sites of particle acceleration than moving interstellar gas clouds. Parker carried out his research on cosmic rays at a time when supernova explosions had not yet been identified as the sources of cosmic rays. However, there was already a widely held view that the majority of cosmic ray particles come to the solar system from interstellar space.

After the discovery of the solar wind, Parker (1965b) realized that the outflowing solar wind would carry turbulent magnetic fields with it and the irregularities in these magnetic fields would act as scattering centres for moving charged particles. The cosmic ray particles have to diffuse through the magnetic irregularities of the solar wind, while being advected with the velocity of the solar wind because of the advection of the magnetic scattering centres with the solar wind. Parker (1965b) showed that the time evolution of the density of the cosmic ray particles would be governed by the Fokker–Planck equation. To make quantitative calculations, the crucial quantity one had to estimate was the diffusion coefficient arising out of the repeated scatterings of the charged particles by the magnetic irregularities in the solar wind. Since the charged particles are expected to diffuse more easily parallel to the large-scale magnetic field of the solar wind than perpendicular to it, the diffusion coefficient is expected to be anisotropic—the coefficient for diffusion parallel to the magnetic field being larger than the coefficient for diffusion in the perpendicular directions. From reasonable assumptions about magnetic irregularities in the solar wind, Parker (1965b) estimated the diffusion coefficients and found them to be in broad agreement with experimental data of cosmic rays.

Later, Jokipii and Parker (1969) developed a more complete theory of how the turbulent velocities in the solar wind would produce stochastic fluctuations in the magnetic field. They realized that the charged particles would tend to gyrate around the large-scale magnetic fields of the Parker spirals. However, due to the scattering from magnetic irregularities, there would be continuous spreading of the cosmic rays in the perpendicular direction. Their calculations of the rate of this perpendicular spreading agreed with experimental data.

6.2 Magnetic flux tubes in the solar convection zone

It is one of the remarkable observational facts that the magnetic fields at the solar surface appear concentrated within structures of different sizes. Sunspots are the largest concentrations of magnetic flux. Big sunspots with magnetic field of about 3000 G can sometimes be so large that it may be possible for the whole Earth to be immersed in one of them. Solar astronomers discovered that magnetic fields outside sunspots exist in the form of smaller magnetic flux tubes having sizes of a few hundred km with magnetic field of the order of 1000 G inside them (Stenflo, 1973). Understanding why magnetic fields at the solar surface exist in the form of flux tubes of different sizes has been a challenge for theoretical MHD and a topic which interested Parker greatly.

Biermann (1941) explained the darkness of sunspots by suggesting that the tension of the magnetic field—which arises out of the term involving $(\mathbf{B}, \nabla)\mathbf{B}$ in (1)—inhibits convective heat transport inside sunspots so that sunspots become cooler than the surroundings. The linear theory of magnetoconvection (i.e. convection in the presence of magnetic fields) was developed by Chandrasekhar (1952), showing that the magnetic field indeed inhibits convection. If magnetic fields are concentrated in some regions inside a convective gas, we certainly expect the convection to be inhibited within those regions. But why should the magnetic field be concentrated in some regions? To address this question, Parker (1963b) carried out some elegant mathematical calculations to study how magnetic fields evolve in regions of stationary fluid flows having some circulatory patterns inside them. He found that magnetic fields tend to get swept away from interior regions of circulatory fluid flow and are concentrated in regions of converging fluid flow, which Parker (1963b) had taken to be vertical. Within a few years of this, Weiss (1966) carried out a numerical simulation to confirm Parker's idea. These demonstrations that magnetic fields become concentrated within regions of converging flow provided the important first step towards understanding how concentrations of vertical magnetic field arise at the top of the solar convection zone.

If magnetic fields are concentrated by converging flows, it is easy to argue that the magnetic energy density $B^2/8\pi$ should at most be of order of the fluid kinetic energy $(1/2)\rho v^2$. However, observational studies of small magnetic flux tubes at the solar surface indicated that the magnetic fields inside them have energy densities a few times larger than the kinetic energy density of surroundings fluids. It was clear that some additional mechanism was needed to concentrate the magnetic field further. Parker (1979b) showed how this may happen by considering a vertical magnetic flux tube in hydrostatic equilibrium. Parker (1979b) argued that downward fluid flows inside such flux tubes may give rise to an instability, leading ultimately to a different configuration of the flux tube with stronger magnetic field inside. This process has been named *convective collapse*. Further analysis of this subject was presented by Spruit (1979) and a numerical simulation was carried out by Hasan (1985).

One other influential work of Parker connected with flux tubes which we would like to mention is his theory of the structure of sunspots. Parker (1978)

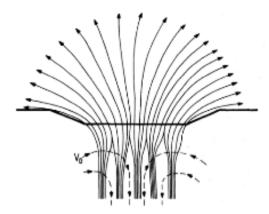


Fig. 12 The fibril structure of sunspots proposed by Parker (1978). Reproduced by permission of the AAS.

pointed out that many aspects of observational data about sunspots can be explained better if a sunspot is a collection of magnetic flux tubes held together rather than a monolithic flux tube. Figure 12 sketches the structure of sunspots Parker (1978) proposed. Further support for this model came when observational study of the emergence of sunspots showed that sunspots often form through the process of smaller flux tubes emerging first and then coming together (Zwaan, 1985).

7 Parker's important non-solar contributions

As already pointed out, Parker had broad interests in plasma astrophysics and did not want to be identified merely as a solar physicist. We have repeatedly emphasized that even Parker's works described in sections 4–6 can be readily applied to those solar-like stars which have magnetic activity like the Sun. We now turn our attention to Parker's other important contributions beyond solar physics.

Before discussing specific research contributions, we take note of the monumental 800-page monograph *Cosmical Magnetic Fields* (Parker, 1979a). Although this large book packed with equations may appear forbidding at first sight, it provides pleasurable reading because of its elegant and clear style of writing. A large part of this classic of plasma astrophysics is devoted to developing many of the basic topics of MHD which have the possibility of wide applications to various astrophysical systems. After developing the basics, Parker (1979a) considers applications to planets, stars and galaxies in the last few chapters. It should be pointed out that to some extent the choice of topics was guided by Parker's own research interest and not all types of astrophysical magnetic fields are covered in this book. For example, there is no discussion about pulsars and their magnetic fields. Although Parker himself had analyzed the problem of magnetic braking of the rotating Sun by the solar wind

Springer Nature 2021 LATEX template



Life and Science of Eugene Parker 33

Fig. 13 The cover of Volume 2 of the Russian translation of Parker's book *Cosmical Magnetic Fields*.

and it was recognized that magnetic braking of protostars is extremely important in the star formation process, curiously there is no discussion of magnetic braking in Parker's book. Some of the important topics of stellar magnetism not included in Parker's book have been discussed in the book by Mestel (1999), another classic volume in the same *International Series of Monographs* on *Physics* in which Parker's book had appeared. It may be mentioned that Parker's book was translated into Russian in two volumes—Volume I translated by A. Ruzmaikin and Volume II by A. Shukurov. The 2-volume set was edited by Ya B. Zeldovich and published in 1982 by Mir Publishers (information about this translation was provided to me by Anvar Shukurov). Parker received these volumes when I was a student in the group. Although he normally would not display his emotions, he was as happy as a child to receive these two volumes and excitedly brought them to my office to show me.

Since much of Parker's non-solar work deals with the magnetic field in the interstellar medium of galaxies, let us first say a few words about the initial history of the subject. Parker himself has provided an account of this early history from his perspective: Parker (1979a), pp. 795–807. The first indication that a magnetic field spans our Galaxy came when Hiltner (1949) discovered the light from many stars to be polarized. Davis and Greenstein (1951) pointed out that a galactic magnetic field must have aligned paramagnetic dust grains so that the interstellar medium acts as a polarizer. Chandrasekhar and Fermi

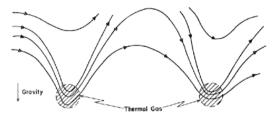


Fig. 14 A figure from the paper on Parker instability (Parker, 1966), sketching how the instability arises as a result of the thermal gas flowing down the magnetic field lines due to gravity to collect in a few clumps in the galactic mid-plane. Reproduced by permission of the AAS.

(1953) were to present one of the first estimates of the strength of the galactic magnetic field based on ingenious theoretical arguments: of order 10^{-6} G. From the polarization data of many stars, it could be inferred that the magnetic field is in the direction of the spiral arm of the Galaxy. One interesting fact became apparent even in the early days of research. The energy densities of the interstellar gas, the magnetic field and the cosmic rays are comparable, there being some kind of equipartition of energy among these various components. We recommend the excellent review by Sofue et al (1986) for a comprehensive discussion about observational data pertaining to magnetic fields of spiral galaxies.

7.1 Parker instability of the interstellar medium

In a series of papers, Parker presented a study of the dynamical system comprising the interstellar gas, magnetic field and cosmic rays in the disk of a galaxy (Parker, 1966). Since the interstellar gas is everywhere at least partially ionized and has reasonably high electrical conductivity, the magnetic field remains frozen into it. The cosmic ray particles gyrate around this magnetic field and are confined by it. As a result, these three components—the interstellar gas, magnetic field and cosmic rays—are coupled to each other and make up one unified dynamical system. Out of these three components, only the gas remains confined within the gravitational potential well of the galaxy. The magnetic field and the cosmic rays are essentially massless, which try to bulge out of the galactic disk without being confined by the gravitational field.

One can think of an equilibrium configuration in which the magnetic field has the form of straight field lines lying in the galactic plane. In the very first paper of the series, Parker (1966) realized that this configuration would be unstable. This instability is nowadays known as the *Parker instability*. The basic physics of this instability can be elucidated on the basis of some qualitative arguments without any detailed mathematical analysis. Suppose the magnetic field has bulged out of the galactic disk in some region. The gas from the upper part of the bulge would flow due to the gravitational field of the galaxy towards the galactic disk. As a result, the upper part of the bulge would become lighter and more buoyant, triggering an instability and rising up further. The gas would keep collecting within the valleys between the bulges, as shown in Figure 14. Eventually the rise of the bulge may be halted by the magnetic tension. It appears from Figure 14 that the resultant configuration may have clumps of gas along the spiral arm of the galaxy. One standard way of studying the interstellar gas in external galaxies is to to use a radio telescope to receive radiation at the 21-cm line of hydrogen. Radio maps of some external galaxies show such clumps of gas along spiral arms, like beads on a string: see, for example, Figure 7 of Rots (1975). The nonlinear evolution and eventual saturation of the Parker instability have been studied through numerical simulation by Mouschovias (1974).

7.2 The galactic dynamo

If one takes the size of a spiral galaxy as the length scale over which the galactic magnetic field varies significantly, then the decay time of the magnetic field turns out to be much larger than the age of the Universe. It may appear at first sight that the galactic magnetic field could therefore be primordial and no mechanism is needed to sustain it. However, the disk of a spiral galaxy undergoes differential rotation, which would be expected to wind up a primordial magnetic field many times till the relevant length scale becomes much smaller and the magnetic field is dissipated. It is clear that a magnetic field extending along the spiral arms of a galaxy could not be primordial and we need something like a dynamo mechanism to sustain the magnetic field in such a configuration.

Parker (1971) carried out an analysis of the dynamo problem in a rectangular slab geometry corresponding to a local region of the galaxy. The differential rotation (which was an uncertain parameter in the solar dynamo problem before the advent of helioseismology) to be used in the analysis can easily be obtained if observational data on the rotation of the galaxy are available. Parker (1971) realized that turbulence in the interstellar gas in the presence of rotation would be helical and the α -coefficient (Parker did not use the symbol α) associated with it would have opposite signs above and below the midplane of the galaxy. Parker (1971) set up the $\alpha\Omega$ dynamo equations within the rectangular slab corresponding to the local region of the galaxy. Since the differential rotation stretches out the magnetic field, the solution suggests a strong toroidal component of the magnetic field—approximately in the direction of the spiral arms as seen in the observational data. Parker estimated the growth time of the dynamo to be of order 10⁸ yr—somewhat smaller than the age of a typical spiral galaxy.

For readers interested in knowing how our understanding of the galactic magnetic field evolved in the subsequent years after the influential work of Parker (1971), we recommend the excellent review by Ruzmaikin et al (1988).

7.3 Parker limit of magnetic monopoles

When Parker was selected for the Henry Norris Russell Lectureship of the American Astronomical Society, he (Parker, 1970) presented a rather intriguing back-of-the-envelope calculation. We take the electric field to be zero inside a conductor while solving an electrostatics problem, because the free electrons inside the conductor can move around and screen the electric field. Similarly, if there were many magnetic monopoles inside a galaxy, they could have neutralized the magnetic field of the galaxy. Parker (1970) realized that the very existence of the galactic magnetic field could be used for arguing that there could not be too many monopoles in the galaxy.

If there were n magnetic monopoles per unit volume with strength g moving with velocity \mathbf{u} , then the rate at which the galactic magnetic field would perform work per unit volume is $ng\mathbf{u}.\mathbf{B}$. The energy for doing this work would surely come from the energy of the galactic magnetic field so that we should have

$$\frac{d}{dt}\left(\frac{B^2}{8\pi}\right) = -ng\mathbf{u}.\mathbf{B}.\tag{13}$$

Note that Parker (1970) overlooked the minus sign in his equation! By demanding that the decay time has to be longer than the growth time of the magnetic field due to some mechanism (like the dynamo mechanism), one can put an upper bound on the value of monopole density n. Parker (1970) estimated $n < 10^{-26}$ cm⁻³. This is now known as the *Parker limit*.

Parker (1970) presented a short (less than one page) discussion of this topic in his Russell Lecture clearly to entertain the audience before he moved into a discussion of more serious stuff. However, when some grand unified theories of particle physics suggested the existence of magnetic monopoles and experiments to detect them were planned in the late 1970s and the early 1980s (Cabrera, 1982), the Parker limit provided important guidance in the design of the experiments. Suddenly the Parker limit became very famous among physicists working in areas of physics far removed from astrophysics or plasma physics who might not know much about Parker's other works. A more detailed analysis of the Parker limit was presented by Turner et al (1982).

8 Gene as a scientist and as a human being

After discussing Gene Parker's science, I shall now present a pen portrait of his personality as a scientist and as a human being.

8.1 Scientist and member of scientific community

Since many of Gene Parker's major scientific papers are noted for the elegance of mathematical analysis, it may seem that the beauty of mathematical physics might have been what motivated Gene to do science. However, he repeatedly told many of us that what motivated him to a scientific pursuit was his desire to understand how things work. When he lived near a railroad yard as a child,

he was fascinated to see locomotives move (Parker, 2014). He was also fascinated by cars and aeroplanes and wanted to understand their basic working principles. This is certainly not unusual for a theoretical physicist, if we think of the example of one of the greatest theoretical physicists of the twentieth century: Richard Feynman, whom Gene admired greatly. Feynman was also driven by a desire to understand how things work.

There were, however, big contradictions in Gene's engagement with technology. It may be expected that somebody who always wanted to understand how things work would pick up new technology fast and would be at home in the new world of computers which unfolded during Gene's career. That was not the case. Although Gene always admitted the importance of numerical simulations and praised those who were good at it, he himself seemed to be rather afraid of computers and was unwilling even to touch one for many years. For nearly a decade after the rest of the world had switched over to email, Gene kept sending hand-written letters via air mail. When Gene finally started using e-mail, I actually felt saddened that I would no longer receive those hand-written letters from him.

Since Gene's research had been exclusively based on classical physics, it may appear that he was temperamentally suited for classical physics. Again, he told me often that quantum mechanics fascinated him when he was a student and he often regretted that his creative career took him along a path in which he never had occasions to use quantum mechanics.

Gene was usually a friendly person who was easy to get along. He generally had good relations with most of his colleagues and fellow scientists in the field. However, sometimes he could be uncompromising when it came to science. He always insisted that scientific ideas should be closely and carefully argued. He stressed the importance of order-of-magnitude estimates to check whether an idea worked or not. He could be very impatient with ideas which he considered fuzzy and nebulous—especially when they were put forth by important persons in a pompous manner. Gene had a famously frosty relationship with Alfvén. He recognized the importance of Alfvén's early contributions to MHD and had also nominated Alfvén for the Nobel Prize in 1964 when he and Chandrasekhar were invited by the Nobel Committee to send nominations. Gene told me that, although his relationship with Alfvén had already somewhat sourced, Chandra persuaded him to nominate Alfvén, arguing that it would be good for their field if Alfvén received the Nobel Prize. In later years, as Gene was highly critical of Alfvén's newer works, their relationship nosedived. Gene was, however, diplomatic enough not to put his criticisms of Alfvén's ideas in his monograph (Parker, 1979a). He simply refrained from commenting on those ideas which he considered irrelevant. While talking to students, Gene often gave the examples of the later Eddington and the later Alfvén, and told us that we should all be careful not to become like them. In a scathing review of Alfvén's book Cosmical Plasmas, Cowling (1982) wrote: "It was, to say the least, surprising to find a book on cosmical plasmas which did not so much as mention the work of E. N. Parker."

Gene was usually kind and encouraging to younger scientists. However, occasionally he had debates with younger scientists as well. As already mentioned in section 5.2, van Ballegooijen (1986) carried out a simulation of the problem which Gene studied in his classic 1972 paper (Parker, 1972)—how the magnetic field between two planes gets distorted by footpoint motions on the planes. Gene thought that the results of the simulation supported his ideas. However, Aad van Ballegooijen himself and some others thought otherwise. From a distance of nearly four decades, now this controversy may appear rather irrelevant to us. However, it rocked the American solar physics community quite a bit in the mid-1980s. When Aad came to give a seminar at the High Altitude Observatory where I was a postdoc, we found that both Aad and I were interested in a common scientific question, which we studied together (van Ballegooijen and Choudhuri, 1988). Perhaps I was the only person having regular academic interactions with both Aad and Gene during the height of their debate. Both of them talked to me a few times about this controversy. Although each of them would firmly express his disagreement with the other, it was a learning experience for me to see that each referred to the other with extreme respect. Gene told me that he regarded Aad to be a brilliant young man and greatly admired his simulations, but was puzzled why And was sticking to what appeared to Gene to be a misjudged interpretation of the simulation results. I know of only one case when Gene was scathing and unsparing in his criticism of a younger scientist. In a paper (Ionson, 1982) which created a buzz at the time of its publication but is almost forgotten now, Jim Ionson claimed that he solved the coronal heating problem by reducing it to the analogue of an LCR circuit. Gene felt that the crucial steps in the derivation of the LCR circuit analogy made no logical sense and were totally unintelligible. It was the type of paper which Gene did not want anybody to write.

Gene was always very open about criticisms of his own work and would readily admit any genuine mistake in his published works if brought to his attention. Bernie Roberts, who was a postdoc with Gene in the 1970s, wrote the following to me in an e-mail dated 12 March 2023:

In my first work suggested by Gene (I published it in ApJ in 1976) I found he had made a mistake in an earlier paper. I didn't know how to tell him this but in the end came up with a diplomatic phrase "this observation means Parker (1974) is redundant". I asked Gene if he was happy with the comment as he made no remark about it whatever in the draft of my paper. He said he was happy with it. I asked again, could he (ENP) have expressed it better. He thought for a few minutes and then said "I would say the man is a bloody idiot!". I have always remembered how he took my correction on the chin, with no excuses offered.

I visited Chicago a little after I was convinced that the $\alpha\Omega$ dynamo model for the solar cycle proposed by Gene could not be the final correct model and important modifications were needed. I have given an account of my conversation with Gene which I shall never forget: see p. 182 of Choudhuri (2015).

Gene's self-effacing nature often produced the opposite of the desired effect. This happened for his 60th birthday meeting organized by some of his colleagues at the University of Chicago. After initially resisting such a meeting, Gene eventually agreed on the condition that it would be a low-key meeting for which only a small number of persons who were close to Gene should be invited. However, as the information about this meeting spread through the community, receiving an invitation for it became a status symbol for some senior solar physicists. I was a postdoc at the High Altitude Observatory (HAO) at that time. One day Peter Gilman working there stormed into my office and asked me if I was invited for this meeting. I told him that I was invited but would not be able to attend it, because I had already promised to join a faculty position in India a few days before the meeting. Peter fumed: "I had worked on some of the same subjects on which Parker worked and I know him personally. I do not understand why a senior person like me in this field is not invited."

I have already mentioned in the Introduction that Gene rarely wrote collaborative papers, most of his papers being single-author. Presumably, the main reason behind this is his highly individualistic style of research. Using deep physical intuition, he would think up a mathematically workable model of something that would capture the essential physics of a complex situation. He enjoyed working on problems of this kind by himself. Also, most of his works did not involve the type of lengthy calculations which he could assign to his students or postdocs (the typical situation in many theoretical physics groups around the world). After finishing the work, Gene would compose his papers with extreme care. Most of his papers are models of scientific writing. Normally we do not talk about the style of a scientist the way we talk about the style of an artist like Van Gogh or Cezanne. But Gene was one rare scientist whose papers can be identified from the style by somebody who is familiar with his papers.

8.2 Teacher and supervisor

Let me say a few words about Gene as teacher. Gene was an enthusiastic teacher who taught the first year graduate level course on electromagnetic theory quite regularly. I am lucky that, during my first year of graduate school, he taught a superb course on plasma astrophysics. It was rather uncommon for American universities in those days to offer a course on plasma astrophysics at the graduate school. I was quite overwhelmed by the beauty of the subject. I was rather undecided till that time as to the area of physics in which I wanted to pursue my research. It was this course on plasma astrophysics taught by Gene which made me decide to work in this field.

Gene was a thorough and meticulous teacher, but not flashy or flamboyant. He would prepare well for his lectures and would cover a huge amount of material in each lecture. His lectures would be very logically structured, with full derivations worked out on the blackboard in a step-by-step manner. Although his lectures might be a little dry, a student who had the necessary prerequisite and followed his classes attentively could get the logical thread of



Fig. 15 Gene Parker with some of his former PhD students at the meeting to celebrate his turning 60. From left to right: Eugene Levy, Tom Bogdan, Parker, Boon Chye Low and Kanaris Tsinganos

arguments. While Gene might not have been the type of teacher whom students usually think of recommending for important teaching awards, he was generally regarded as one of the good teachers in the department whose courses were extremely useful.

Since Gene was a very individualistic scientist who mostly worked on his own, one might wonder how he was as a supervisor. Gene always enjoyed having young persons around, with whom he could talk about many things. When applying for research grants, he would always ask for funds to support students or postdocs. His group was never large. During the four years I worked in his group, he usually would have two young persons in the group—either two graduate students or one graduate student and a postdoc. Gene had 14 graduate students over his career, whom he had listed in Parker (2014). I come towards the end, being his 11th student. Gene mentioned that he continued to have regular ineractions with four of his students over the years after the completion of their PhD (Parker, 2014). I am lucky to belong to this privileged group along with B.C. Low, Kanaris Tsinganos and Tom Bogdan. It may be pointed out that Gene's first student graduated in 1963. This means that he had no student working with him when his famous theory of the solar wind was worked out.

When I first started thinking of working with Gene after attending his course on plasma astrophysics, some of the senior astrophysics students cautioned me that, although Gene was a superb scientist and superb teacher, he did not have the reputation of being a good research supervisor. After I started working with Gene, I realized that these senior students had a valid point. It

was not easy to be a student of Gene. He worked on his own and wanted the young persons in his group also to work on their own. Gene was a very easily approachable person, whom one could meet virtually any time without an appointment when he was in his office. He enjoyed discussing science with his students. However, apart from suggestions of very broad and general nature about what he considered some of the important unsolved problems of solar MHD which one could try working on, he never suggested any specific wellformulated research problems—at least to me. I have to confess that I had to struggle quite a bit before I could form some idea of how one selects research problems. At one stage, when nothing seemed to work, I thought of quitting research in astrophysics. Gene persuaded me to continue with his kind words and encouragement, although he still would not suggest a definite research problem. I have given an account of my experience of working with Gene in my popular science book: see pp. 122–126 of Choudhuri (2015).

Being very particular about the composition of scientific papers, Gene would always read the manuscripts of the young persons in his group very carefully. When the young person would get back the manuscript, it would usually be heavily annotated with suggestions for both science and style. Gene regarded this to be the normal duty of a senior scientist and never expected to be a co-author for such help.

8.3 Beyond science

Gene was a kind and gentle person who always enjoyed hiding his gentleness underneath an external image of being a no-nonsense tough guy. It is not easy to come across such a down-to-earth person who was so exceptionally free from all kinds of snobbery. His assessment of other human beings would always be completely free from biases of social status, position, race, gender Gene was also a very strong man, who jogged regularly and walked extremely fast. I would usually try to avoid walking with Gene over considerable distances. Although I was in my twenties when I was a student at Chicago and Gene was in his fifties, I would be panting to keep pace with him. It would be very embarrassing! Arieh Königl, who joined as assistant professor at the Universiy of Chicago when I was a student there, wrote to me in an e-mail on 17 March 2022:

Regarding Gene's athletic prowess, my own story goes back to my one-day visit to the Department as a faculty candidate, when Gene served as my host. I carried a small suitcase and he just grabbed it and started running up the stairs, with me in toe. I thought to myself at the end of the day that, irrespective of how my job interview would go, I could get back home and brag that, for one whole day when I was in Chicago, Gene Parker had carried my suitcase!

A further note on this story: Even though I only had one day, Gene didn't think he needed to take me to see yet another lab or office; instead, he reckoned (correctly!) that he could impress me even more by taking me to visit the Oriental Institute – which is what he did.



Fig. 16 Some of Gene Parker's remarkable wood carvings. Credit: Eric Parker.

The Oriental Institute, later renamed the Institute for the Study of Ancient Cultures, in a central location in the University of Chicago campus is an outstanding museum of archaeological specimens from West Asia and North Africa—mostly discovered by Chicago archaeologists.

Gene took a conscious decision that after retirement in 1995 he would not pursue his regular astrophysics research and devoted time to his other interests. He would write only a very occasional regular scientific paper when some scientific question occupied his mind. However, on a few occasions, he agreed to write reviews on different aspects of plasma astrophysics—some of them being of historical nature. He also wrote the charming little book Conversations on Electric and Magnetic Fields in the Cosmos (Parker, 2007), which shows his sense of humour even when discussing science. Gene would spend many pleasurable hours of his retired life on his other passion: wood carving. He started on wood carving many years before his retirement. He acquired an immense skill for it as he started spending many hours on wood carving after retirement. Apart from a few persons close to Gene, most members of the scientific community who had admired Gene's science over the years would not know about this other aspect of Gene's interest. Gene would never make a public display of his artistic talent and never kept any of his wood carvings in his office. I saw some of his wood carvings for the first time when I had an opportunity of visiting his home and was completely amazed by the professional perfection with which they were executed. Gene could probably make a living as a professional artist with his wood carvings if he wished. A few selected pieces of his wood carving are shown in Figure 16.

The two great towering figures of theoretical astrophysics at Chicago— Chandra and Parker—had one common talent in spite of the many differences in their personalities. Both of them were great story-tellers with amazing memory. Both could vividly describe with colourful details some incident which they had witnessed many years ago. Gene had a great talent for imitating other people's speaking styles.



Fig. 17 Gene Parker with Asian scientists. (i) Lecturing at the Indian Institute of Astrophysics, Bangalore. (ii) With Japanese scientist K. Shibata. (iii) With P.-F. Chen in China.

I realize that I have never talked with Gene about religion and do not know his views on it. I always presumed that he did not have much interest in religious matters. Gene had extremely liberal views on politics. Ronald Reagan was the American President during the years when I was working with Gene for my PhD. He would often make scathing remarks about Reagan's policy of interference in the countries of Central America. He had a tremendous sympathy for people who lived under difficult circumstances in different parts of the world. The Soviet Union fascinated him. He had a great respect for the physics research tradition of that country. A few years before the breakup of the Soviet Union (when I was a student at Chicago), Gene had an opportunity of attending a conference in the Crimean region and also visited the astrophysics institute at Irkutsk in the middle of Siberia. On his return, Gene excitedly described to me his experience of visiting the Soviet Union and told me some anecdotes about Zeldovich, whom Gene admired deeply and was looking forward to meet.

Since this paper is written for a journal brought out by the Association of Asia-Pacific Physics Societies, I end this pen portrait of Gene by mentioning that he had a special soft corner for the Asia-Pacific region. Japan has a long tradition of astrophysics research, including solar physics. However, when Gene began his scientific career, no other Asian country had any significant group for solar physics research. It was during the scientific career of Gene that solar physics research began in countries like India, China and Korea. Gene was a keen observer of these developments and was always willing to help solar physicists working in these countries. Although Gene did not like to travel much, he would never give up an opportunity of vising an Asian country. Figure 14 shows several photographs of Gene Parker with Asian scientists. Many solar physicists in different Asian countries told me about Gene's kindnesses and encouragement to their fledgling scientific communities. When I decided to return to India after spending seven years in the USA, academic salaries in India were typically about one-tenth of the salaries for corresponding positions in the USA. Most of my well-wishers in the USA advised me against this move, which they considered suicidal. Gene was one lone person in the USA who stood by my side in that difficult decision, as described in pp. 133–134 of Choudhuri (2015).

9 Concluding remarks

We have provided a brief account of Gene Parker's life and discussed some of his major scientific achievements. In the field of solar MHD, his works provided the connecting threads among different aspects of solar activity and transformed the field into a logically coherent subject. He also made fundamental contributions outside solar physics—especially in our understanding of the galactic magnetic field. Our discussion of Gene's science should make it clear why he is regarded as the most impact-making and tallest figure in the field of plasma astrophysics. I have also tried to present a pen portrait of Gene indicating his very unique way of approaching science.

As expected, Gene Parker received many high accolades during his academic career. Here is a partial list of some of the most important academic honours bestowed on him: Russell Lectureship (1969); Hale Prize (1978); Maxwell Prize (2003); Kyoto Prize (2003); Alfvén Prize (2012); APS Medal for Exceptional Achievement (2018); Crafoord Prize (2020). There are many speculations why he was not given the Nobel Prize. As these speculations are not based on documentary evidence, we refrain from discussing them. Since Gene was a self-effacing person who never blew his own trumpet, during much of his life, he was not known outside the community of astrophysicists as much as he should have been known. However, towards the tail end of his life, he suddenly came close to becoming a public figure when he turned out to be the first living person after whom NASA named an important mission: the Parker Solar Probe! When this Probe was launched on 12 August 2018, Gene was already over 91. Still he travelled to Cape Canaveral with his family to see the launch of the Probe.

Gene generally enjoyed reasonably good health till a couple of years before his passing away, when deteriorating Parkinson's disease made it impossible for him to type, which meant that he could no longer exchange e-mails with his well-wishers. He spent the last years of his life in an assisted living facility near the University of Chicago campus, where he passed away peacefully, leaving behind Niesje, his wife for more than 67 years. Niesje passed away on 21 November 2023—some 20 months after Gene's passing away.

Let me end by quoting the message Gene sent on the occasion of an international Workshop held in Jaipur in connection with my turning 60. He wrote:

Let me take this festive occasion to congratulate you on a long and distinguished research career. I remember your early discussion with Chandra on the cultural differences between scientists in the east and the west. Chandra was initially vexed with your analysis but soon admitted that you had a valid point. Only a great scientist like Chandra would recognize the validity of the "upstart" view of an "upstart" student. Those were great days and you did not waste any time in getting on with your research once you had your degree.

Your treatise THE PHYSICS OF FLUIDS AND PLASMAS has proved to be a classic, of which you can be proud. And of which I can be proud that you were once my student who then moved on to another book and a long distinguished research career. We all salute you.

Gene was referring to some ideas put forth in Choudhuri (1985) with which Chandra could not agree. I treasure the above statement from Gene.

Acknowledgments. I thank Mitsuru Kikuchi for inviting me to write this review. The account of Parker's personal life given here would not have been possible without extensive inputs from Eric Parker. Our thanks go to Susan Kane-Parker for organizing and preserving Gene Parker's personal letters to his parents. I am grateful to Tom Bogdan and Boon Chye Low for many email exchanges about various aspects of Parker's science. I thank Peter Cargill, Marc Kaufman, Arieh Königl, Eric Priest, Bernie Roberts, Anvar Shukurov and Kanaris Tsinganos for valuable discussions. Gopal Hazra and Bibhuti Kumar Jha helped me in preparing this manuscript. Suggestions from two anonymous referees helped in improving the manuscript. The Honorary Professorship offered by the Indian Institute of Science supported my research. A large part of this review was written during my stay at the Max Planck Institute for the History of Science. I thank the Alexander von Humboldt Foundation for sponsoring my visit and thank Alex Blum for stimulating academic discussions.

Declarations

Conflict of interest Arnab Rai Choudhuri is an editorial board member for Reviews of Modern Plasma Physics and was not involved in the editorial review or the decision to publish this article. The author declares that there are no other competing interests.

References

- Alfvén H (1943) On the Existence of Electromagnetic-Hydrodynamic Waves. Arkiv for Matematik, Astronomi och Fysik 29B:1–7
- Alfvén H (1947) Magneto hydrodynamic waves, and the heating of the solar corona. Mon. Not. R. Astron. Soc.107:211. https://doi.org/10.1093/mnras/ 107.2.211
- Alfvén H (1950) Cosmical electrodynamics (Clarendon Press, Oxford)
- Babcock HW (1961) The Topology of the Sun's Magnetic Field and the 22-YEAR Cycle. Astrophys. J.133:572–587. https://doi.org/10.1086/147060
- Biermann L (1941) Der gegenwärtige Stand der Theorie konvektiver Sonnenmodelle. Vierteljahresschrift der Astronomischen Gesellschaft 76:194–200
- Biermann L (1948) Uber die Ursache der chromosphärischen Turbulenz und des UV-Exzesses der Sonnenstrahlung. Zeits. f. Astrophysik25:161

- Biermann L (1951) Kometenschweife und solare Korpuskularstrahlung. Zeits. f. Astrophysik29:274
- Cabrera B (1982) 1st results from a superconductive detector for moving magnetic monopoles. Phys. Rev. Lett.48(20):1378–1381. https://doi.org/10. 1103/PhysRevLett.48.1378
- Caligari P, Moreno-Insertis F, Schussler M (1995) Emerging Flux Tubes in the Solar Convection Zone. I. Asymmetry, Tilt, and Emergence Latitude. Astrophys. J.441:886. https://doi.org/10.1086/175410
- Carrington RC (1859) Description of a Singular Appearance seen in the Sun on September 1, 1859. Mon. Not. R. Astron. Soc.20:13–15. https://doi.org/ 10.1093/mnras/20.1.13
- Chamberlain JW (1960) Interplanetary Gas.II. Expansion of a Model Solar Corona. Astrophys. J.131:47. https://doi.org/10.1086/146805
- Chandrasekhar S, Fermi E (1953) Magnetic Fields in Spiral Arms. Astrophys. J.118:113. https://doi.org/10.1086/145731
- Chapman S (1957) Notes on the solar corona and the terrestrial ionosphere. Smithsonian Contributions to Astrophysics 2:1-14
- Charbonneau P (2010) Dynamo Models of the Solar Cycle. Living Rev Solar Phys 7:3. https://doi.org/10.12942/lrsp-2010-3
- Charbonneau P (2014) Solar Dynamo Theory. Ann. Rev. Astron. Astrophys.52:251–290. https://doi.org/10.1146/ annurev-astro-081913-040012
- Choudhuri AR (1985) Practising Western science outside the West: Personal observations on the Indian scene. Social Studies of Science 15:475–505
- Choudhuri AR (1989) The evolution of loop structures in flux rings within the solar convection zone. Solar Phys.123:217–239. https://doi.org/10.1007/BF00149104
- Choudhuri AR (1998) The physics of fluids and plasmas : an introduction for astrophysicists (Cambridge: Cambridge University Press)
- Choudhuri AR (2010) Astrophysics for Physicists (Cambridge University Press)

- Choudhuri AR (2011) The origin of the solar magnetic cycle. Pramana 77:77–96. https://doi.org/10.1007/s12043-011-0113-4, https://arxiv.org/abs/arXiv:1103.3385 [astro-ph.SR]
- Choudhuri AR (2014) The irregularities of the sunspot cycle and their theoretical modelling. Indian Journal of Physics 88:877–884. https://doi.org/ 10.1007/s12648-014-0481-y, https://arxiv.org/abs/arXiv:1312.3408 [astroph.SR]
- Choudhuri AR (2015) Nature's third cycle: a story of sunspots (Oxford University Press). https://doi.org/10.1093/acprof:oso/9780199674756.001.0001
- Choudhuri AR (2017) Starspots, stellar cycles and stellar flares: Lessons from solar dynamo models. Science China Physics, Mechanics, and Astronomy 60(1):19601. https://doi.org/10.1007/s11433-016-0413-7, https://arxiv.org/abs/arXiv:1612.02544 [astro-ph.SR]
- Choudhuri AR (2023) The emergence and growth of the flux transport dynamo model of the sunspot cycle. Reviews of Modern Plasma Physics 7(1):18. https://doi.org/10.1007/s41614-023-00120-9, https://arxiv.org/abs/arXiv:2212.14617 [astro-ph.SR]
- Choudhuri AR, Schüssler M, Dikpati M (1995) The solar dynamo with meridional circulation. Astron. Astrophys.303:L29–L32
- Choudhuri AR, Chatterjee P, Jiang J (2007) Predicting Solar Cycle 24 With a Solar Dynamo Model. Physical Review Letters 98:131103. https://doi.org/ 10.1103/PhysRevLett.98.131103, https://arxiv.org/abs/astro-ph/0701527
- Cowling TG (1933) The magnetic field of sunspots. Mon. Not. R. Astron. Soc.94:39–48. https://doi.org/10.1093/mnras/94.1.39
- Cowling TG (1953) Solar Electrodynamics. In: Kuiper GP (ed) The Sun. p 532
- Cowling TG (1982) A review of: "Cosmical plasmas". Geophysical and Astrophysical Fluid Dynamics 21(3):324–327. https://doi.org/10.1080/03091928208209024
- Davis JLeverett, Greenstein JL (1951) The Polarization of Starlight by Aligned Dust Grains. Astrophys. J.114:206. https://doi.org/10.1086/145464
- D'Silva S, Choudhuri AR (1993) A theoretical model for tilts of bipolar magnetic regions. Astron. Astrophys.272:621–633
- Dungey J (1953) Conditions for the occurrence of electrical discharges in astrophysical systems. Philosophical Magazine 44(354):725–738

- Durney BR (1995) On a Babcock-Leighton dynamo model with a deep-seated generating layer for the toroidal magnetic field. Solar Phys.160:213–235. https://doi.org/10.1007/BF00732805
- Edlén B (1943) Die Deutung der Emissionslinien im Spektrum der Sonnenkorona. Mit 6 Abbildungen. Zeits. f. Astrophysik22:30
- Elsasser W (1946) Induction effects in terrestrial magnetism .1. theory. PHYS-ICAL REVIEW 69(3-4):106–116. https://doi.org/10.1103/PhysRev.69.106
- Fan Y (2021) Magnetic fields in the solar convection zone. Living Reviews in Solar Physics 18(1):5. https://doi.org/10.1007/s41116-021-00031-2
- Fan Y, Fisher GH, Deluca EE (1993) The Origin of Morphological Asymmetries in Bipolar Active Regions. Astrophys. J.405:390. https://doi.org/10. 1086/172370
- Fermi E (1949) On the Origin of the Cosmic Radiation. Physical Review 75(8):1169–1174. https://doi.org/10.1103/PhysRev.75.1169
- Ferraro VCA (1937) The non-uniform rotation of the Sun and its magnetic field. Mon. Not. R. Astron. Soc.97:458. https://doi.org/10.1093/mnras/97. 6.458
- Forbush SE (1954) World-Wide Cosmic-Ray Variations, 1937-1952. J. Geophys. Res.59(4):525–542. https://doi.org/10.1029/JZ059i004p00525
- Glatzmaier GA, Roberts PH (1995) A three-dimensional self-consistent computer simulation of a geomagnetic field reversal. Nature377(6546):203–209. https://doi.org/10.1038/377203a0
- Gringauz KI, Bezrokikh VV, Ozerov VD, et al (1960) A Study of the Interplanetary Ionized Gas, High-Energy Electrons and Corpuscular Radiation from the Sun by Means of the Three-Electrode Trap for Charged Particles on the Second Soviet Cosmic Rocket. Soviet Physics Doklady 5:361
- Hale GE (1908) On the Probable Existence of a Magnetic Field in Sun-Spots. Astrophys. J.28:315. https://doi.org/10.1086/141602
- Hale GE, Ellerman F, Nicholson SB, et al (1919) The Magnetic Polarity of Sun-Spots. Astrophys. J.49:153. https://doi.org/10.1086/142452
- Hasan SS (1985) Convective instability in a solar flux tube. II Nonlinear calculations with horizontal radiative heat transport and finite viscosity. Astron. Astrophys.143(1):39–45
- Hess V (1912) Observations in low level radiation during seven free balloon flights. Physikalische Zeitschrift 13:1084–1091

- Hiltner WA (1949) Polarization of Light from Distant Stars by Interstellar Medium. Science 109(2825):165. https://doi.org/10.1126/science.109.2825. 165
- Ionson JA (1982) Resonant electrodynamic heating of stellar coronal loops an LRC circuit analog. Astrophys. J.254:318–334. https://doi.org/10.1086/ 159736
- Jokipii JR (1971) Propagation of cosmic rays in the solar wind. Reviews of Geophysics and Space Physics 9:27–87. https://doi.org/10.1029/ RG009i001p00027
- Jokipii JR, Parker EN (1969) Stochastic Aspects of Magnetic Lines of Force with Application to Cosmic-Ray Propagation. Astrophys. J.155:777. https: //doi.org/10.1086/149909
- Kiepenheuer KO (1953) Solar Activity. In: Kuiper GP (ed) The Sun. p 322
- Krause F (1993) The Cosmic Dynamo: From $t = -\infty$ to Cowling's Theorem. A Review on History. In: Krause F, Radler KH, Rudiger G (eds) The Cosmic Dynamo: IAU Symposium no. 157, p 487
- Kuiper GP (1953) The Sun (The University of Chicago Press)
- Kuperus M, Ionson JA, Spicer DS (1981) On the theory of coronal heating mechanisms. Ann. Rev. Astron. Astrophys.19:7–40. https://doi.org/10. 1146/annurev.aa.19.090181.000255
- Leer E, Holzer TE, Fla T (1982) Acceleration of the solar wind. Space Science Rev.33(1-2):161–200. https://doi.org/10.1007/BF00213253
- Leighton RB (1969) A Magneto-Kinematic Model of the Solar Cycle. Astrophys. J.156:1–26. https://doi.org/10.1086/149943
- Low BC (2023) Topological nature of the parker magnetostatic theorem. Physics of Plasmas 30(1). https://doi.org/10.1063/5.0124164
- Lyot B (1939) The study of the solar corona and prominences without eclipses (George Darwin Lecture, 1939). Mon. Not. R. Astron. Soc.99:580. https://doi.org/10.1093/mnras/99.8.580
- Mestel L (1968) Magnetic braking by a stellar wind-I. Mon. Not. R. Astron. Soc.138:359. https://doi.org/10.1093/mnras/138.3.359
- Mestel L (1999) Stellar magnetism (Clarendon Press, Oxford)
- Moffatt HK (1978) Magnetic field generation in electrically conducting fluids (Cambridge University Press)

- Moreno-Insertis F (1986) Nonlinear time-evolution of kink-unstable magnetic flux tubes in the convective zone of the sun. Astron. Astrophys.166(1-2):291–305
- Mouschovias TC (1974) Static Equilibria of the Interstellar Gas in the Presence of Magnetic and Gravitational Fields: Large-Scale Condensations. Astrophys. J.192:37–50. https://doi.org/10.1086/153032
- Obridko VN, Vaisberg OL (2017) On the history of the solar wind discovery. Solar System Research 51(2):165–169. https://doi.org/10.1134/ S0038094617020058
- Pallavicini R, Golub L, Rosner R, et al (1981) Relations among stellar X-ray emission observed from Einstein, stellar rotation and bolometric luminosity. Astrophys. J.248:279–290. https://doi.org/10.1086/159152
- Parker EN (1955a) Hydromagnetic Dynamo Models. Astrophys. J.122:293– 314. https://doi.org/10.1086/146087
- Parker EN (1955b) The Formation of Sunspots from the Solar Toroidal Field. Astrophys. J.121:491. https://doi.org/10.1086/146010
- Parker EN (1957) Sweet's Mechanism for Merging Magnetic Fields in Conducting Fluids. J. Geophys. Res.62(4):509–520. https://doi.org/10.1029/ JZ062i004p00509
- Parker EN (1958) Dynamics of the Interplanetary Gas and Magnetic Fields. Astrophys. J.128:664. https://doi.org/10.1086/146579
- Parker EN (1963a) Interplanetary dynamical processes (Interscience Publishers, New York)
- Parker EN (1963b) Kinematical Hydromagnetic Theory and its Application to the Low Solar Photosphere. Astrophys. J.138:552. https://doi.org/10.1086/ 147663
- Parker EN (1964) The Solar Wind. Scientific American 210.4:66–76
- Parker EN (1965a) Dynamical Theory of the Solar Wind. Space Science Rev.4(5-6):666-708. https://doi.org/10.1007/BF00216273
- Parker EN (1965b) The passage of energetic charged particles through interplanetary space. Planetary and Space Science 13(1):9–49. https://doi.org/ 10.1016/0032-0633(65)90131-5
- Parker EN (1966) The Dynamical State of the Interstellar Gas and Field. Astrophys. J.145:811. https://doi.org/10.1086/148828

- Parker EN (1970) The Origin of Magnetic Fields. Astrophys. J.160:383. https://doi.org/10.1086/150442
- Parker EN (1971) The Generation of Magnetic Fields in Astrophysical Bodies. II. The Galactic Field. Astrophys. J.163:255. https://doi.org/10.1086/ 150765
- Parker EN (1972) Topological Dissipation and the Small-Scale Fields in Turbulent Gases. Astrophys. J.174:499. https://doi.org/10.1086/151512
- Parker EN (1975) The generation of magnetic fields in astrophysical bodies. X Magnetic buoyancy and the solar dynamo. Astrophys. J.198:205–209. https://doi.org/10.1086/153593
- Parker EN (1978) Hydraulic concentration of magnetic fields in the solar photosphere. VI. Adiabatic cooling and concentration in downdrafts. Astrophys. J.221:368–377. https://doi.org/10.1086/156035
- Parker EN (1979a) Cosmical magnetic fields: Their origin and their activity (Clarendon Press, Oxford)
- Parker EN (1979b) Sunspots and the physics of magnetic flux tubes. I. The general nature of the sunspots. Astrophys. J.230:905–923. https://doi.org/ 10.1086/157150
- Parker EN (1983) Magnetic Neutral Sheets in Evolving Fields Part Two-Formation of the Solar Corona. Astrophys. J.264:642. https://doi.org/10. 1086/160637
- Parker EN (1988) Nanoflares and the Solar X-Ray Corona. Astrophys. J.330:474. https://doi.org/10.1086/166485
- Parker EN (1989) Tangential discontinuities and the optical analogy for stationary fields II. The optical analogy. Geophysical and Astrophysical Fluid Dynamics 45(3):169–182. https://doi.org/10.1080/03091928908208898
- Parker EN (1993) A Solar Dynamo Surface Wave at the Interface between Convection and Nonuniform Rotation. Astrophys. J.408:707. https://doi. org/10.1086/172631
- Parker EN (1994) Spontaneous current sheets in magnetic fields : with applications to stellar x-rays (Oxford University Press)
- Parker EN (1996) S. Chandrasekhar and Magnetohydrodynamics. Journal of Astrophysics and Astronomy 17(3-4):147–166. https://doi.org/10.1007/ BF02702301

- Parker EN (2007) Conversations on Electric and Magnetic Fields in the Cosmos (Princeton University Press)
- Parker EN (2014) Reminiscing my sixty year pursuit of the physics of the Sun and the Galaxy. Research in Astronomy and Astrophysics 14(1):1-14. https://doi.org/10.1088/1674-4527/14/1/001
- Petschek HE (1964) Magnetic Field Annihilation. In: NASA Special Publication, vol 50. p 425
- Pneuman GW, Kopp RA (1971) Gas-Magnetic Field Interactions in the Solar Corona. Solar Phys.18(2):258–270. https://doi.org/10.1007/BF00145940
- Pontin DI, Priest ER (2022) Magnetic reconnection: MHD theory and modelling. Living Reviews in Solar Physics 19(1):1. https://doi.org/10.1007/ s41116-022-00032-9
- Priest E (2014) Magnetohydrodynamics of the Sun (Cambridge University Press). https://doi.org/10.1017/CBO9781139020732
- Priest E, Forbes T (2000) Magnetic Reconnection (Cambridge University Press)
- Priest ER (1982) Solar magnetohydrodynamics (D. Reidel, Dordrecht)
- Raouafi NE, Matteini L, Squire J, et al (2023) Parker Solar Probe: Four Years of Discoveries at Solar Cycle Minimum. Space Science Rev.219(1):8. https://doi.org/10.1007/s11214-023-00952-4, https://arxiv.org/abs/arXiv:2301.02727 [astro-ph.SR]
- Rots AH (1975) Distribution and kinematics of neutral hydrogen in the spiral galaxy M81. II. Analysis. Astron. Astrophys.45:43–55
- Ruzmaikin A, Sokolov D, Shukurov A (1988) Magnetism of spiral galaxies. Nature336(6197):341–347. https://doi.org/10.1038/336341a0
- Sakurai T (1985) Magnetic stellar winds: a 2-D generalization of the Weber-Davis model. Astron. Astrophys.152:121–129
- Schatzman E (1962) A theory of the role of magnetic activity during star formation. Annales d'Astrophysique 25:18
- Schwarzschild M (1948) On Noise Arising from the Solar Granulation. Astrophys. J.107:1. https://doi.org/10.1086/144983
- Shibata K, Magara T (2011) Solar Flares: Magnetohydrodynamic Processes. Living Reviews in Solar Physics 8(1):6. https://doi.org/10.12942/ lrsp-2011-6

- Sofue Y, Fujimoto M, Wielebinski R (1986) Global structure of magnetic fields in spiral galaxies. Ann. Rev. Astron. Astrophys.24:459–497. https://doi.org/ 10.1146/annurev.aa.24.090186.002331
- Spruit HC (1979) Convective collapse of flux tubes. Solar Phys.61(2):363–378. https://doi.org/10.1007/BF00150420
- Spruit HC (1981) Motion of magnetic flux tubes in the solar convection zone and chromosphere. Astron. Astrophys.98:155–160
- Steenbeck M, Krause F (1969) Zur Dynamotheorie stellarer und planetarer Magnetfelder I. Berechnung sonnenähnlicher Wechselfeldgeneratoren. Astronomische Nachrichten 291:49–84. https://doi.org/10.1002/asna. 19692910201
- Steenbeck M, Krause F, Rädler KH (1966) Berechnung der mittleren Lorentz-Feldstärke v X B für ein elektrisch leitendes Medium in turbulenter, durch Coriolis-Kräfte beeinflußter Bewegung. Zeitschrift Naturforschung Teil A 21:369. https://doi.org/10.1515/zna-1966-0401
- Stenflo JO (1973) Magnetic-Field Structure of the Photospheric Network. Solar Phys.32(1):41–63. https://doi.org/10.1007/BF00152728
- Sweet PA (1958) The Neutral Point Theory of Solar Flares. In: Lehnert B (ed) Electromagnetic Phenomena in Cosmical Physics: IAU Symposium no. 6, p 123
- Turner MS, Parker EN, Bogdan TJ (1982) Magnetic monopoles and the survival of galactic magnetic fields. Physical Review D 26(6):1296–1305. https://doi.org/10.1103/PhysRevD.26.1296
- van Ballegooijen AA (1986) Cascade of Magnetic Energy as a Mechanism of Coronal Heating. Astrophys. J.311:1001. https://doi.org/10.1086/164837
- van Ballegooijen AA, Choudhuri AR (1988) The Possible Role of Meridional Flows in Suppressing Magnetic Buoyancy. Astrophys. J.333:965. https:// doi.org/10.1086/166805
- Wang YM, Sheeley NRJr., Nash AG (1991) A new solar cycle model including meridional circulation. Astrophys. J.383:431–442. https://doi.org/10.1086/ 170800
- Weber EJ, Davis JLeverett (1967) The Angular Momentum of the Solar Wind. Astrophys. J.148:217–227. https://doi.org/10.1086/149138
- Weiss NO (1966) The Expulsion of Magnetic Flux by Eddies. Proceedings of the Royal Society of London Series A 293(1434):310–328. https://doi.org/

10.1098/rspa.1966.0173

- Yoshimura H (1975) Solar-cycle dynamo wave propagation. Astrophys. J.201:740–748. https://doi.org/10.1086/153940
- Zwaan C (1985) The Emergence of Magnetic Flux. Solar Phys.100:397. https://doi.org/10.1007/BF00158438