The mercurial Sun at the heart of our solar system

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As the powerhouse of our solar system, the Sun's electromagnetic planetary influences appear contradictory. On the one hand, the Sun for aeons emitted radiation which was "just right" for life to evolve in our terrestrial Goldilocks zone, even for such complex organisms as ourselves. On the other, in the dawn of Earth's existence the Sun was far dimmer than today, and yet evidence for early liquid water is written into geology. Now in middle age, the Sun should be a benign object of little interest to society or even astronomers. However, for physical reasons yet to be fully understood, it contains a magnetic machine with a slightly arrhythmic 11 year magnetic heartbeat. Although these variations require merely 0.1% of the solar luminosity, this power floods the solar system with rapidly changing fluxes of photons and particles at energies far above the 0.5eV thermal energy characteristic of the photosphere. Ejected solar plasma carries magnetic fields into space with consequences for planets, the Earth being vulnerable to geomagnetic storms. This chapter discusses some physical reasons why the Sun suffers from such ailments, and examine consequences through time across the solar system. A Leitmotiv of the discussion is that any rotating and convecting star must inevitably generate magnetic "activity" for which the Sun represents the example *par excellence.*

Introduction

The present paper attempts to introduce astronomers concerned with exo-planetary studies to electromagnetic solar influences on its planetary system. The approach follows that of a recent book [1], presenting a viewpoint of a physicist and astronomer, not of a solar specialist. Table 1 lists gross solar properties, which could be used together with elemental abundances and data from elementary physics, to construct a theoretical star of the kind shown in Figure 1. But this fictional star merely reflects a star without magnetic fields. Magnetism arises from the differential motions of ions and electrons within plasmas like the Sun, and because there are no magnetic charges (monopoles), magnetic fields are not shorted out, and can pervade plasmas. In contrast, large-scale electric fields cannot be supported in plasmas. The interactions between solar plasma and magnetism constitutes the main focus of interest in modern solar physics. The clearest signature of magnetism in stars and the Sun is in spots (Figure 2). Not only are these much darker than the granulated surface, but by using polarized light the magnetic flux can be measured through the Zeeman effect (a technique started by Hale and colleagues [2, 3]).

The present discussion encompasses the Sun's behavior as it affects the solar

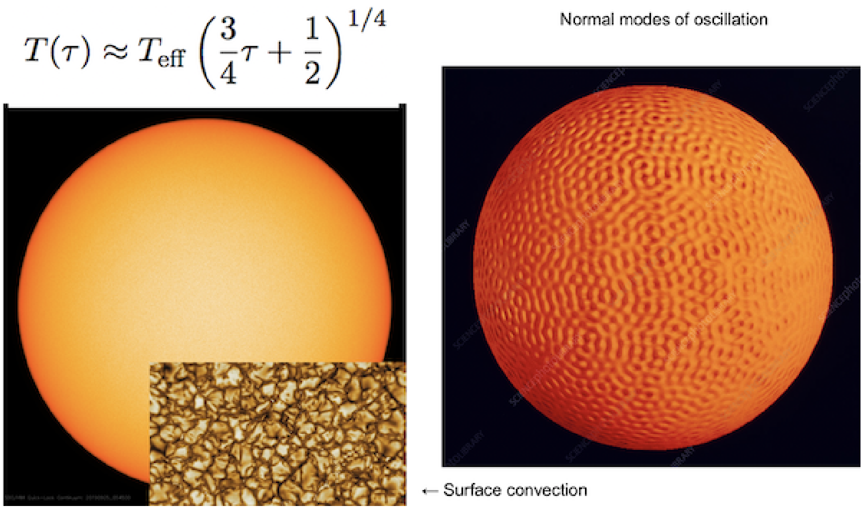

Fig. 1. A fictional star without magnetic fields. The equation shows the run of temperature with grey optical depth τ for a radiative equilibrium atmosphere. The left panel shows limb darkening and surface convection, with roughly 4 million granules on the solar surface at any moment. The right panel shows Doppler shifts associated with the incoherent superposition of normal modes of oscillation. The solar rotation is seen as an East-West gradient, spanning $\pm$ 2 km s^{-1}.

system, from zero-age main sequence to the present day and beyond. On timescales short compared with thermonuclear processing, this magnetic "activity" is responsible for electromagnetic disturbances perturbing the planets. Over 5 decades, solar and stellar studies reveal that magnetically-induced solar variations associated with sunspots are not exceptional among the stars. It is, however, somewhat *mercurial*[a]: on the one hand the well-known sunspot cycle (an aspect of which is shown in Figure 3) is the most regular 11-year cyclic variation of all stars [4]. On the other, these cycles are punctuated by irregular epochs of weakened magnetic influences on timescales of centuries. Dynamic, unpredictable flares often associated with coronal mass ejections (CMEs) vary over timescales of minutes [5]. CMEs are magnetized bubbles of energetic plasma into interplanetary space unleashed by the Sun, frequently with consequences for a society dependent on a stable global electromagnetic environment [5]. The precise mechanisms underlying this behavior remain beyond current understanding. However, some of the ingredients that are known are discussed in an Appendix, acknowledging that non-linear and non-local physical effects still present us with significant fundamental challenges. Thus our understanding is still largely driven by observations and not from consideration of first-principles. This argument applies both to the regeneration of global solar

[a] A character described as changeable; volatile; lively; sprightly; fickle; flighty; erratic. From Greek mythology.

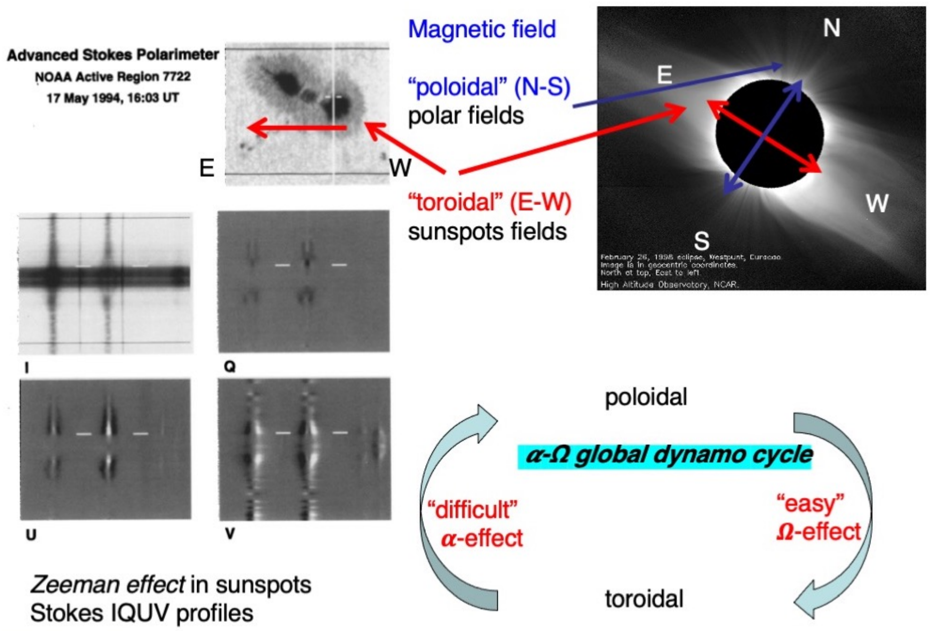

Fig. 2. The images reveal observational signatures of solar magnetic fields. Outside of sunspots magnetism is best detected through the polarization of light by the Zeeman effect. Sunspots themselves are aligned mostly E-W and are believed to originate from the emergence of tori of magnetic field generated by differential rotation of fluid in the solar convection zone (Ω-effect). Polar magnetic fields are traced by coronal plasma along N-S oriented rays in the coronal image. The schematic "dynamo cycle" of magnetic field is illustrated demonstrating the continuous process of generating poloidal fields (seen at the pole) from toroidal fields (sunspots), and vice versa.

magnetism discussed in the appendix, as well as effects such as coronal heating and dynamics (e.g., [6].)

Table 1. Some basic properties of the Sun

Age	4.54 Gyr
Mass $M_\odot$	2×10^{30} kg
Radius $R_\odot$	700,000 km
Distance	150,000,000 km $\equiv$ 1 AU
Luminosity $L_\odot$	4×10^{26} W
Irradiance at Earth	1.365 kW m^{-2}
Average rotation period*	27 days
Tilt of rotation axis to ecliptic	7°
Stellar spectral type	G2 V
$B - V$ color	0.65
Absolute magnitude M_V	4.83

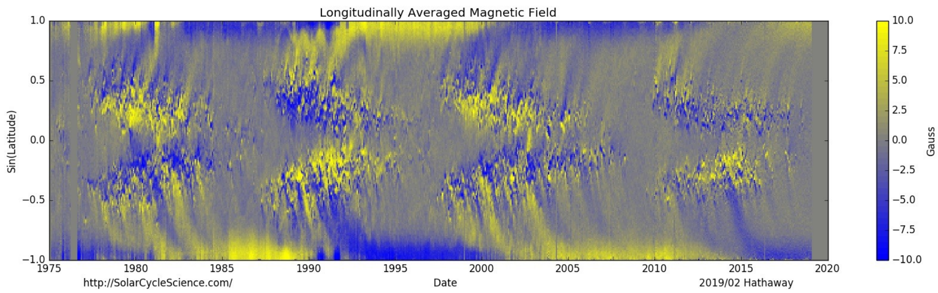

Fig. 3. The signed surface magnetic flux densities (units Mx cm^{-2}) are shown as a function of time and latitude, derived from Stokes V profiles of spectral lines (lower right spectral image in Figure 2). Poloidal components are seen as the yellow and blue patches close to the two poles, and the (mostly) toriodal fields are seen in the "butterfly wings" which are mostly oriented E-W (Figure 2). Between these, surface fields propagate towards the poles, mostly of opposite polarity to the polar fields, appearing to reverse the polarity of polar fields every 11 years. The butterfly wing pattern was originally discovered by Annie and Edward Maunder in 1904.

*The surface rotates differentially, from 25 days at the equator to over 30 days near the poles.

A non-magnetic Sun

A fictional Sun-like star without magnetic fields (Figure 1) has benign influences on its planetary system:

- The star brightens on the main sequence by just 13% per Gyr, with a ZAMS effective temperature $T_{\rm eff}$ of 5660 K, increasing by $\approx$ 25 K per Gyr.
- The planets are irradiated by a near black-body spectrum with temperature near $T_{\rm eff}$.
- These irradiances would be weakly modulated by small amplitude random variations of surface convection (granules) on periods between 2 and 10 minutes, and the linear oscillations of normal modes of oscillation of the elastic sphere, peaked near periods of 5 minutes [7].

This fictional star would provide a stable input to interplanetary space over aeons, conducive to the slow evolution of life, necessary perhaps to develop complex multicellular life like ourselves [8]. It would possess no reservoir to store free energy in its atmosphere outside of those in fluid wave modes, and emit almost no UV or X-radiation. In stark contrast, Figure 4 also shows solar spectra between the maxima and minima of the 11 year cycle of sunspots, as black and blue lines respectively. No solar magnetism means no ionosphere.

Magnetic Sun

The reasons why the Sun must behave according to Figures 2-4 are by no means obvious, either from a theoretical (see the Appendix) or empirical point of view.

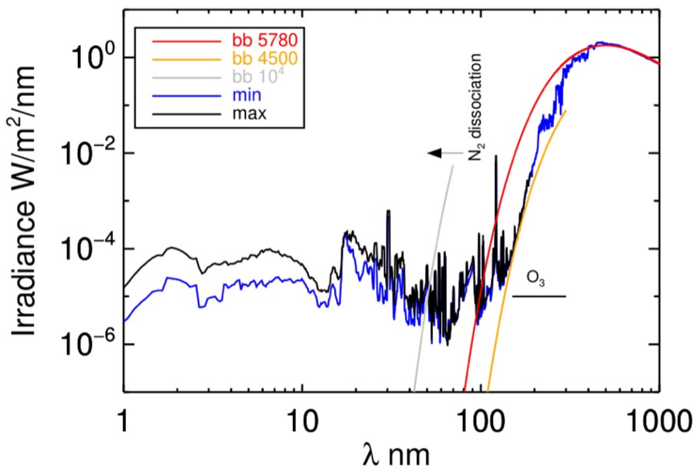

Fig. 4. Five flux spectra relevant to Sun-like stars are shown. Smooth lines show black body spectra. The blue line is a reference spectrum measured close to minimal solar magnetic activity [9], the black a representative spectrum close to sunspot maximum. The arrow indicates wavelengths at which the N_2 molecule, dominant in the thermosphere, is photo-dissociated, indicating that a non-magnetic Sun would possess no permanent ionosphere. However, stratospheric ozone (O_3) would be formed in either case.

For example, there exist rapidly-rotating Sun-like stars without spot cycles, with more energetic magnetic fields and lacking the level of symmetry exhibited in time and space by the Sun in Figure 3. Sun-like stars can show spots on rotational time scales (weeks) but with no sunspot cycles (e.g., [4]).

The solar magnetic fields can usefully be projected on to poloidal and toroidal components (Figure 2, see also the Appendix), which are convenient also for modeling solar magnetic evolution (e.g., [10].) In the context of models described in the Appendix, the solar cycle involves the repeated interplay between the toroidal and poloidal fields on a time scale of 11 years. Some effects of these variable surface magnetic fields are highlighted in Figure 5, showing an image of the solar disk seen in the resonance line of He^+ (orange) at 30.4 nm. It is seen as a prominent peak along with the H Lα line at 121.6 nm in the flux (irradiance) spectra shown in Figure 4. These lines arise from plasma close to 100,000 and 20,000 K respectively. It also shows the solar corona close to 1 million K observed in broad-band light (darker orange), both images from instruments on the SoHO spacecraft. The dark orange "ear-like" structure is a coronal mass ejection (CME) extending over a solar radius above the surface. CMEs are enormous, hot magnetic plasmoids arising from and separated from the Sun by magnetic reconnection [5, 11]. The right half of the figure shows a sketch (not to scale) of the CME later as it has propagated through interplanetary space (diffuse tan), energetic particles (white dots), the Earth's magnetosphere (blue), and the CME as it later impacts the magnetopause region of Earth's atmosphere. The cartoon shows a quiescent phase before the blue (magnetospheric) and tan (CME) magnetic fields interact. More consequential are those phases where the CME plasma gains entry into the Earth's magnetosphere through magnetic reconnection at the interface region ("magnetopause") and in the stretched out tail of the magnetosphere, causing potentially damaging geomagnetic storms.

These phenomena all arise from the storage and release of magnetic free energy in the corona, caused by the emergence and perturbation of magnetic fields generated by dynamo action in the solar interior [12]. The measured irradiation

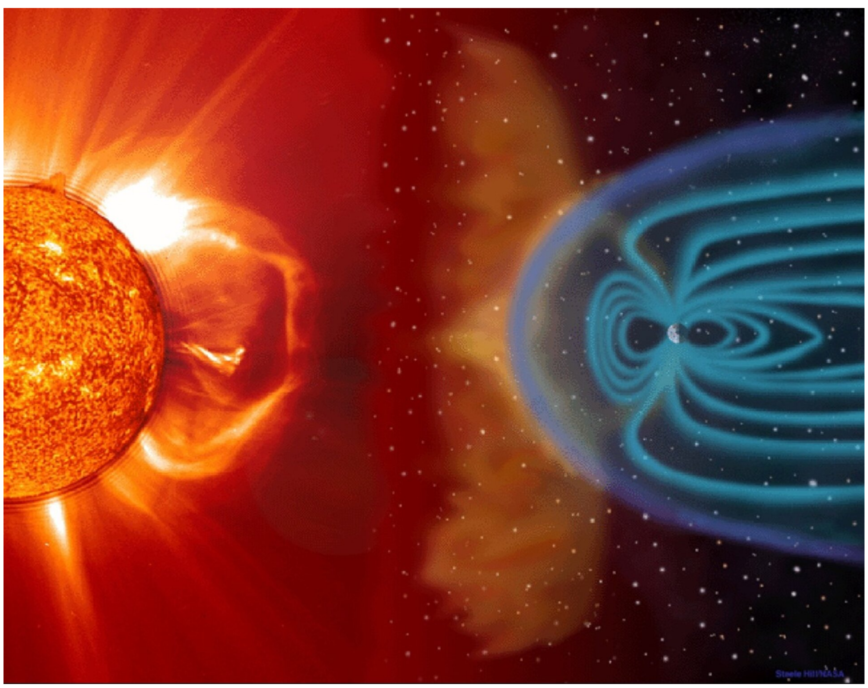

Fig. 5. Two images of the real Sun observed by instruments on the SoHO spacecraft are shown (left) along with a sketch (not to scale) of the Earth and its magnetosphere (right). A non-magnetic star would show neither the solar disk nor corona, could not produce energetic particles (white dots) or a mass ejection, and the Earth's magnetosphere would be unperturbed. Figure produced by ESA.

of the solar system varies on all time scales from seconds (flares) to decades (the waxing and waning of sunspots). Representative variations over decades are shown in Figure 4, showing typical solar spectra in blue and black lines, representative of a minimum and maximum in the number of spots on the Sun. These changes occur on a timescale of just 5 years! The figure also shows that little of the entire solar luminosity is carried shortward of 200 nm, but that the variations in the irradiance increase systematically with decreasing wavelength. Soft X-rays of 1 keV energy (wavelengths near 1 nm) vary over decades almost by a factor of 10 as sunspots come and go. By comparison, the *total* (wavelength-integrated irradiance as measured at Earth) varies only by about 0.1%. However, the passage of a single large sunspot group over several days can change the total irradiance for days by 1%. Numbers of short-lived but highly energetic solar flares and CMEs are statistically correlated with sunspot numbers [13], during which the EUV and X-ray irradiances can increase by orders of magnitude over minutes and hours. Later we will see that the Sun can produce far more energetic flares than have yet been recorded.

In short, the differences between the fictional star and the Sun indicate that

> *the Sun is a machine which generates magnetic fields, with a strong 22 year periodicity. The evolving magnetism emits high energy radiation and plasma particles into interplanetary space, which fluctuate on timescales down to minutes.*

The Appendix summarizes what this remarkable solar behaviour implies about underlying physical causes.

The Sun, stars, and life on Earth

We inhabit a planet around an ordinary, middle-aged star in the outer parts of an ordinary spiral galaxy. Even before the first detections of extrasolar planets, astronomical evidence (for example, in the distribution of elemental abundances), together with the remarkable success of the theory of stellar evolution (e.g., [14]), suggests that the solar system is an ordinary and natural product of stellar and galactic evolution. It arose from the debris of earlier generations of ordinary massive stars which lived their whole lives in the Galaxy. In terms of universal life, and assuming (as usual) that the laws of nature are universal, this mundane situation raises profound philosophical questions: is life nevertheless so rare that our solar system is the only place in the universe with life? Or is life teeming across the universe [8], in which case, where is everyone (a question attributed to Enrico Fermi in 1950)?

After Earth's formation, bombardments, tectonic activity and the acquisition of water, the Earth entered a phase of relative stability suitable for the early creation of life. Threats to life over the following aeons include variations in global climate, asteroid and meteoroid collisions, and, perhaps, high energy events from the Sun. The remains of this discussion asks, *how did the Sun's magnetic machinery evolve, and could there have been important consequences for evolution of complex life on Earth?* After all, high energy electromagnetic disturbances were essential components leading to "primordial soup" of amino acids from inorganic ingredients in the famous Miller-Urey experiments in the 1950s.

In this "big picture" view, I am struck by a poetic parallel which can be drawn between planetary and stellar magnetism. After the formation of the first stars,

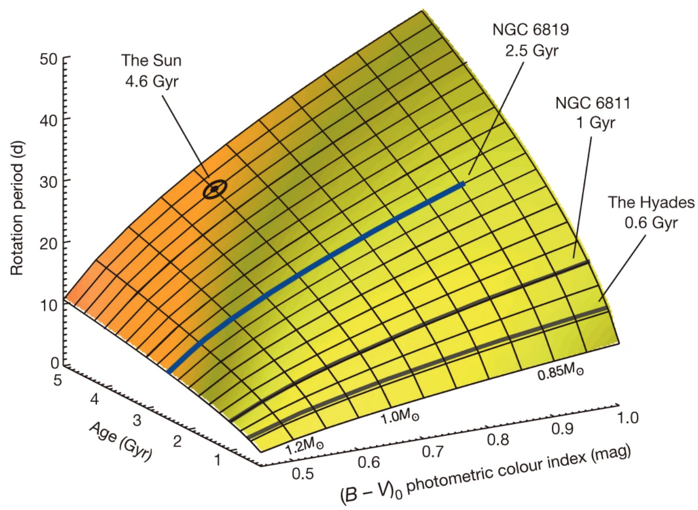

Fig. 6. A modern summary of relations between stellar rotation and age. For each color index, a single curve along the surface gives the empirical rotation - age relationship. Measurements of rotation period can thus be used to estimate stellar ages, a method termed "gyro-chronology". Figure taken from [15].

young massive stars converted primordial H, He and a trace of Li into the array of elements generated both by fusion and neutron capture processes. Thanks in part to the decay of radioactive elements like ^{232}U in the interior, the Earth's core is heated, and in part, molten and subject to convection. Coupled with Earth's rotation, Walter Elsässer [16] first suggested that the convecting fluid then generates its own magnetic field. serving as a protective shield against hostile energetic charged particles of cosmic and solar origins. Thus, while the Sun's magnetised fluid generates threats, the Earth naturally generates a natural defense, through the same kind of mechanism (a dynamo). The story of stellar rotation and associated magnetic evolution on the main sequence is also, perhaps a poem of epic proportions:

- Rotation and convection are natural consequences of the formation and evolution of stars,
- these are the essential ingredients to generate global and variable global magnetic fields (Appendix), then
- an increase in temperature is an unavoidable consequence of the motions of emerging magnetic fields and ion-neutral collisions [17], so that
- all the elementary physical ingredients are naturally available to generate a magnetically active corona [18], then

- the pressure of hot coronal plasma leads to expansion that cannot be contained by the interstellar medium, causing the solar wind [19], and then
- the magnetic torque exerted by the Sun on the rotating, frozen-in wind plasma then slows solar rotation, and finally
- on main sequence lifetimes, the slower rotation weakens the magnetic fields generated in the interior.

This story, based on first principle ideas. is borne out by data. Beginning with the work of Skumanich in 1975 [20], the rotation rates Ω of Sun-like stars were related to stellar age t as

$$\Omega(t) \propto t^{-1/2}, \tag{1}$$

based upon just four data points (open cluster stars and the Sun). The recent advent of asteroseismological stellar age determinations from missions such as Kepler and TESS has vastly extended Skumanich's early picture, from a single relation $\Omega(t)$ to dependencies on more variables. As an example. $\Omega(t, [B-V]_0)$, for main sequence stars, is shown in Figure 6.

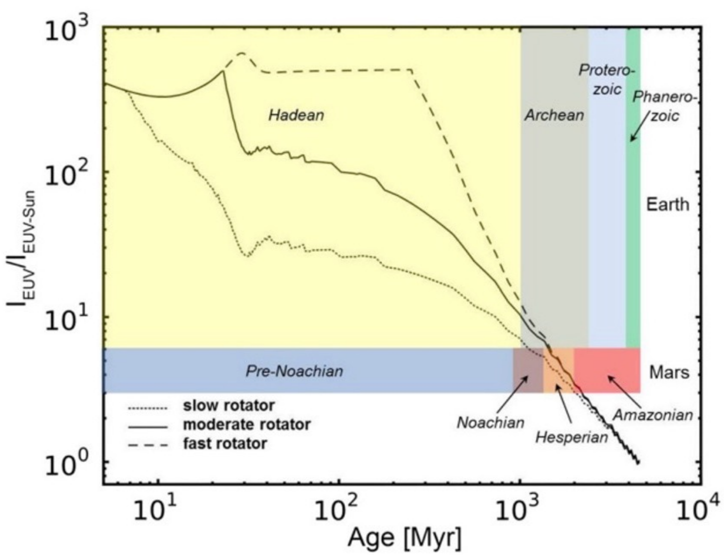

Fig. 7. Three possible histories of high energy (EUV) radiation of the Sun are plotted, depending on the assumed zero age main sequence rotation rate. The "Skumanich" law, derived from data between 40 and 4000 Myr, would be a straight line with slope -1/2 in this plot. Various eras in the histories of Earth and Mars are indicated. The earliest fossil evidence for life on Earth is dated at 3465 Myr ago, an age of ≈ 1080 Myr, defining the beginning of the Archean era. Figure taken from [21].

Armed with data from a variety of spacecraft over decades, we can consequently infer that the early Sun flooded the solar system with far more intense UV and X- radiation than it does today. Figure 7 is a recent representation of possible histories of high energy radiation of Sun-like stars with age on the main sequence. The implications of this story of solar rotation are explored further in the next section.

A closer look

Stars like the Sun

The Sun does not belong to any known stellar group, but it is similar to the stars in the open cluster M67. Gyro-chronology suggests an age of 4 Gyr for the stars of M67. The Sun is 4.54 Gyr old (Table 1). The cluster is too distant (800-900 pc) to observe G2 V stars at UV and X-ray wavelengths ($m_V \approx 14.5$). Thus we are left to compare the Sun's magnetic activity mostly with nearer, brighter field stars.

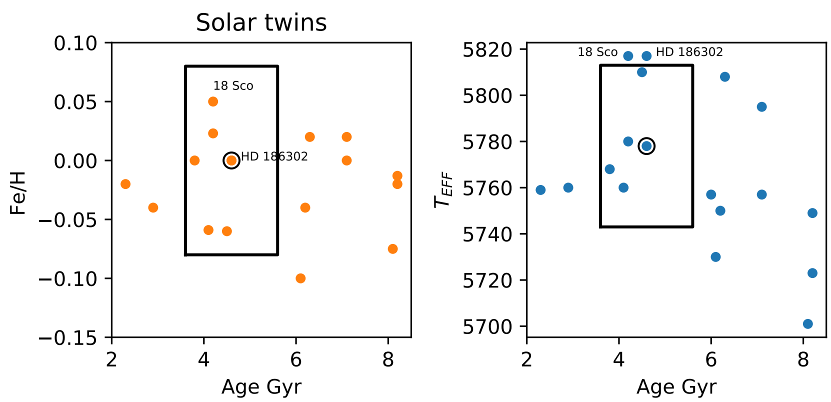

Fig. 8. Known solar twin candidates are plotted in terms of metallicity (left panel) and effective temperature (right panel) as a function of stellar age. The Sun is shown as an open black circle. Estimates of typical uncertainties are represented by the black box. The data are taken from `https://en.wikipedia.org/wiki/Solar_analog`.

Many authors have sought a genuine "twin" for the Sun among the stars. Currently the best candidates are HD 146233 (18 Sco) and HD 186302 (https://en.wikipedia.org/wiki/Solar_analog). A group of genuine "solar twin" would be of enormous practical use and interest in our quest to relate solar behavior to other stars. Genuine twins would permit us to assess if there are any special properties about the Sun. However, nature presents us with challenges:

- The Sun is "old" in the sense that spin-down by angular momentum loss has already occurred at 4.5 Gyr sufficient to have erased any "memory" of the ZAMS angular momentum. (Figure 7). As such it is therefore magnetically

"inactive" among its younger stellar relatives, and it is not highly luminous in UV or X-ray wavelengths.
- While there are ≈ 500 stars in our immediate neighborhood ($d \leq 30$ pc), they reflect the known initial mass distributions and so of these, only about 25 are G stars of luminosity class V. Of these only about 13 have spectral types between G0 and G4.
- The dimensionality of a "Sun-like" space of variables is a little subjective. But this space must contain at least ZAMS mass, metallicity, age and rotation rate. Figure 8 reveals the dearth of possible candidates in two scatter plots.

Not only are there few twin candidates, but the typical uncertainties are large: 4-5 different stars are identical with the Sun within the uncertainties. But this situation is expected to improve as Sun-like stars become the focus of the large number of exoplanetary scientists.

Stars of solar mass through time

Again our focus is on magnetic activity and not stellar evolution *per se*. Researchers have documented not only the high energy emission, but also bulk wind properties using observations at visible, UV to X- ray wavelengths. Nice reviews are available from Güdel [22, 23]. Figure 9 highlights how high and low energy emission evolves in time, as represented by surface flux density measurements of several stars of $1_{\odot}$. The harder the radiation, the faster it decays with age. The generic "EUV" emission (wavelengths between about 10 and 91 nm) used in the geospace community cannot be measured for enough stars owing to large Lyman-continuum optical depths in the interstellar medium. The "EUV" emission presumably lies between the UV and X-ray behaviours shown. The very steep trends in UV emission and X-ray emission are somewhat different, the latter indicating that coronal soft X-ray emission cannot exceed a limit near $2 \cdot 10^{30}$ erg, $6 \cdot 10^{7}$ erg cm^{-2}s^{-1}, or 0.005 $L_{\odot}$. This "saturation" has been known for almost 4 decades, but the underlying reasons are still debated. Note that the present day Sun's 100nm UV spectrum (emission lines and continua are both important for upper atmospheric chemistry and dynamics) is some 1 and 2 orders of magnitude weaker than stars of age 2 Gyr and 0.1 Gyr respectively.

The (non-linear) dynamical responses of the Earth's atmosphere to between 1 and 10 times the mean solar EUV flux have been studied [24, 25]. The Earth's atmosphere does not blow off (i.e. the thermal energy at the "exobase" does not exceed a critical fraction of the gravitational potential energy). This is because hydrodynamic flow and adiabatic expansion sap the available energy for heating the upper atmosphere for levels of EUV flux 5 times those of the mean present-day Sun. In contrast Mars would have lost any initial atmosphere, only able to maintain a warm and wet period several hundred Myr after Mars formed (see Figure 7) when the EUV fluxes dropped within an order of magnitude of the current Sun [26].

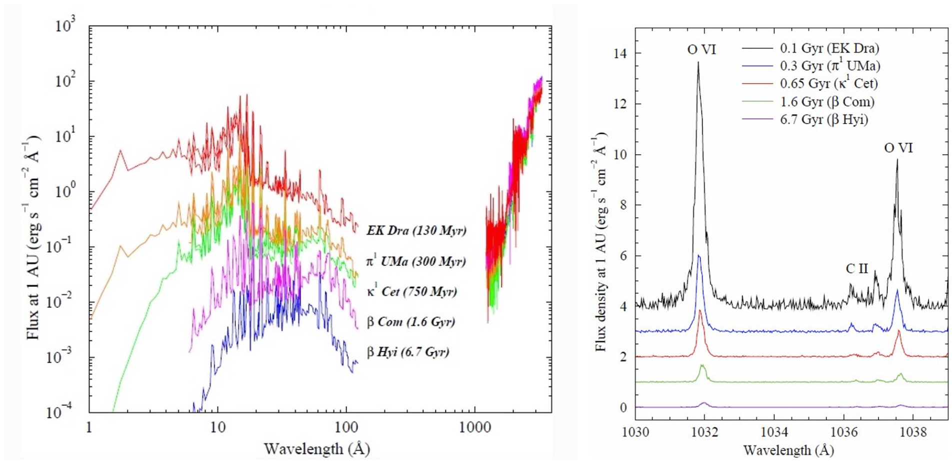

Fig. 9. Levels of emission from Sun-like stars are shown as a function of age on the main sequence. Flux densities at the stellar surface can be derived by multiplying by $(1\mathrm{AU}/R_\odot = 215)^2 = 4.6{\cdot}10^4$. Note the logarithmic and linear scales plotted, and the gap between 120 and 1000 Å caused by interstellar absorption. Figures from [22].

Flares and CMEs

The above arguments rely on data from "typical" observations, not those rarer phenomena such as flares. Again, a vast quantity of data has been analyzed for the Sun [27] and significant progress again has been made with recent photometric asteroseismology missions for sun-like stars [28]. One might expect that flaring might higher in intensity and frequency in younger stars. The story is even now unfolding as recent satellite databases undergo more and more scrutiny. Flares recorded on Sun-like stars (Figure 10) extend far higher in energy than the largest in solar history [29], the "Carrington Event" of 1959, with an estimated energy of 10^{33} ergs. Flares last shorter than 24 hours, so that while the impact of flare radiation on surface life might be serious on the illuminated hemisphere, areas in shadow would not receive devastating doses of high energy radiation. We can speculate that this intermittent source of energy on genetic mutations might have been relevant to the evolution of complex life on Earth.

Conclusions

Absent from this brief discussion is the importance of understanding why the Sun is obliged to produce sunspots with the pulse of a 22 year cycle (Figures 2, 3). Hopefully ground-based observations of chromospheric Ca^+ lines begun in 1966 will continue over many more decades [4] and for more stars, to improve our knowledge of what might cause and then suppress cycling behavior, for stars having the same convection and rotation properties. The answer to why the Sun and a few stars must do this is central to our understanding of magnetic evolution, also giving

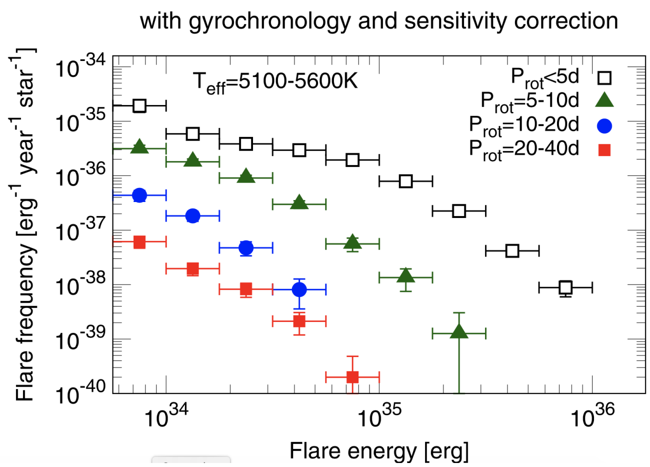

Fig. 10. The occurences of flares on Sun-like stars from the Kepler mission are shown as a function of flare energy in several stellar age bins. The strongest ever ("Carrington") flare of 1859 is estimated to have released about 10^{33} erg. The figure suggests that a flare of 10^{34} erg might occur once every 2000 years or so on the present Sun. In contrast, at 1 Gyr (a rotation period near 10 days) this flare would occur once every 30 years or so. Figure from [28].

insight into the weaker pulse of of sunspot signals during the Maunder Minumum (1645-1715, [30]). Curiously, the Sun presents the most ordered 22-year cycle of all field G stars, only about 10% of which show clear cycles [4]. Young field G stars tend to show strong irregular variability, old stars weak, if any, secular variations. In terms of cycle properties, the Sun is more similar to field K stars.

The magnetic machinery of Sun-like stars is only partly understood from first principles. Neither the operation modes of the global dynamo or the manner in which energy is released in the atmosphere with accompanying high energy particles and radiation are understood. They are relatively well documented in our observations. But because of the enormous challenges facing theorists, solar physics will continue to be an observationally-driven field. The place of the Sun among the stars will remain of central interest to our understanding of astrophysical dynamos and plasma physics, and it will become clearer as our datasets improve.

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Appendix: The Sun's magnetic engine

There is no reason *a priori* that the Sun should behave in this fashion. Although the required power of all this "activity" is a small fraction of the total solar luminosity, the oscillatory behaviour has garnered attention of physicists. This behavior is striking because the implied magnetic *order* exists in spite of the fact that energy transport across the outer 28% of the Sun, by radius, is dominated by turbulent convection. Perhaps solar magnetism is a manifestation of *emergent* behavior arising from the complexity of a complex dynamical system [31]. Alternatively, a more deterministic mechanism might be in action, perturbed by convection to produce the "noise" seen, for example, in Figure 3, and others. The latter picture is almost universally adopted by solar physicists, and is adopted below because it has value pedagogically.

Much observational evidence and physical considerations strongly argue in favor of the regeneration of magnetic fields within the solar interior (e.g., [12].) Since 1989, one critical ingredient of deterministic models has been measured through observations of the modulation of the Sun's normal modes of oscillation ("helioseismology"). Until measurement of the internal profile for axial differential rotation $\Omega_\varphi(r, \vartheta)$ as a function of radius r and latitude ϑ were available, only the *surface* and coronal rotation properties were accessible to observers. Helioseismology has identified three interior regions The solar interior has three shear layers in the inte-

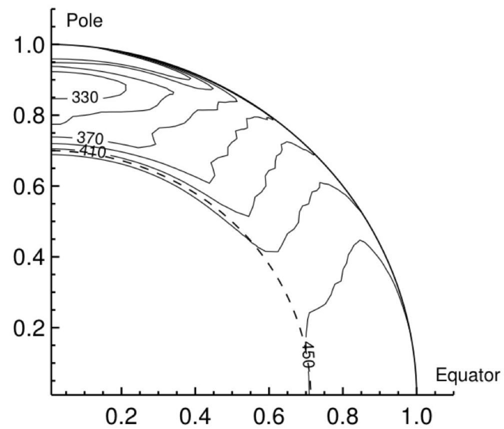

Fig. 11. The figure shows the internal rotation rates *in the toroidal direction* of the solar interior as a function of radius and latitude as derived from helioseismology. The lines are contours of constant rotation rate in units of 10^{-9} Hz. The closely packed contours in the figure are favourable locations for the amplification of magnetic fields through the Ω-effect. Data from [1].

rior (Figure 11). Radial shears in Ω_φ are found just below the convection zone (the "tachocline") and just beneath the photosphere. A latitudinal shear is found near latitudes of $|\vartheta| = 55°$. These large-scale shear zones can readily generate toroidal magnetic fields by stretching magnetic field lines around the axis of rotation. Called the Ω-effect, these shears are believed to be a critical component of credible large-scale, dynamos (see Figure 2). But in order to make the Sun's magnetism oscillate, another effect is needed, and one example of a model is discussed briefly here, the α-effect.

To complete a deterministic model requires ingredients in addition to the helioseismic large-scale shear motions (e.g. [32]):

- sources and sinks of magnetic fields are needed to produce repetition over 22 years,
- processes that convert poloidal fields to toroidal fields are needed, which must
- break cylindrical symmetry [33].

Asymmetries in the internal fluid dynamics arise directly from rotation, because the Coriolis force ($-2\rho\ \mathbf{\Omega} \times \mathbf{u}$) that acts upon convective flows of density ρ and velocity $\mathbf{u}$, is a pseudo-vector, i.e. asymmetric under reflection. To proceed further, we can consider the Sun as a magneto-hydrodynamic (MHD) system (e.g. [34]).

The magnetic field then evolves according to the *induction equation*[b]:

$$\frac{\partial \mathbf{B}}{\partial t} = \mathbf{curl}\,(\mathbf{u} \times \mathbf{B}) + \eta \nabla^2 \mathbf{B}, \quad \eta = 1/\mu_0 \sigma, \tag{2}$$

where σ is a scalar electrical conductivity and μ_0 the permeability of free space. To zeroth order the observations indicate that global surface magnetic fields (the left hand side of equation 2) must change on time scales of a decade. Kinetic theory gives us fluid transport coefficients such as conductivities σ [35], from which $\eta \sim 1$ m^2 s^{-1} in the Sun's interior. Choosing $\ell \sim R_\odot/3 = 2 \times 10^8$ cm, the diffusive term in equation (2) has a time scale of $\ell^2/\eta \sim 10^9$ years! Evidently, the "advective" term $\mathbf{curl}\,(\mathbf{u} \times \mathbf{B})$ must not only provide a source, but also must drive a sink for magnetic fields when integrated over the volume of the Sun. Correlations and anti-correlations between $\mathbf{u}$ and $\mathbf{B}$ can lead both to positive and negative contributions to equation (2). Such correlations must operate on spatial scales $\ll R_\odot$ in order to produce time scales of years, but must have consequences on global length scales. Inspired by Parker's notion of small-scale convective cyclonic turbulence [32] one class of dynamo model seeks solutions to the development of large-scale vector fields $\overline{\mathbf{X}}$, $\mathbf{X} = \overline{\mathbf{X}} + \mathbf{X}'$, where the vector field $\mathbf{X}$ is assumed to be consist of separate large and small scales $\overline{\mathbf{X}}$ and $\mathbf{X}'$. The small-scale correlations are averaged out and written in terms of tensor coefficients, and the reader is referred to an excellent review by Rempel summarizing further ideas [36]. Of the various tensor coefficients, the most important here is α which appearing as a source term in the poloidal magnetic field which is otherwise absent (e.g., [10]).

$$\frac{\partial \overline{\mathbf{B}}}{\partial t} = \ldots + \mathbf{curl}\,\left(\alpha \overline{\mathbf{B}}\right) = \ldots + \alpha \mu_0 \bar{\mathbf{j}}\,, \tag{3}$$

i.e. the induced magnetic field induced by motions contributing to α is proportional to the mean current, completing the "circuit" shown in Figure 2. Rempel [36] shows that, when stratification exists (under a gravity vector $\mathbf{g}$), then

$$\alpha \approx \alpha_0(\mathbf{g} \cdot \mathbf{\Omega}) = \tau_c^2 v_{\rm rms}^2 \mathbf{\Omega} \cdot \mathbf{grad}\, \ln(\varrho v_{\rm rms}), \tag{4}$$

where the rms turbulent speed u_{rms} and turnover time τ_c characterize the turbulence, and α_0 is a constant. Note that $Ro = (\Omega \tau_c)^{-1}$ is the well-known "Rossby" number. In short, we have physical ingredients to generate a cycling dynamo, summarized as follows (see Figure 2):

$$\mathbf{B}_p \xrightarrow{\Omega} \mathbf{B}_t \xrightarrow{\alpha} \mathbf{B}_p \xrightarrow{\Omega} \mathbf{B}_t \ldots, \tag{5}$$

where both the α and Ω model parameters depend on the timescales for rotation, differential rotation and convection. In summary, observations can constrain physical models of evolving solar magnetism, suggesting that the quasi-deterministic

[b] A combination of Ohm's law, Faraday's law of electromagnetic induction, Ampére's law and the lowest order transformation of electric fields in the frame of the fluid moving with velocity $\mathbf{u}$)

picture has some merit. The native asymmetries, the roles of rotation and differential rotation are all essential components that are reasonably well understood. However helioseismology, while resolving the solar interior, has also shown more recently that subsurface convective motions u_{rms} are at least an order of magnitude weaker (at $r \approx 0.96 R_{\odot}$) than theory suggests [37, 38], which if confirmed begs the worrying question of what transports the solar luminosity there. Nevertheless it must generate some α-effect and link large- and small- scales through non-linear terms that may be deterministic only in a global (i.e. highly-averaged) sense. For more details including the fascinating global problem of secular hemispheric accumulation of magnetic helicity in such models [39], and non- mean-field models, such as the Babcock-Leighton picture where the α effect takes place primarily in surface dynamics, the reader can should consult modern reviews, for example [36, 40].