Published in: Planetary Influence on the Sun and the Earth, and a Modern Book-Burning, ed. by Nils-Axel Mörner, 2015, Nova Publishers, pp. 91-108.

CHAPTER 8

The Origin of Solar Activity: Local Thermonuclear Runaways in Hot Bubbles and Their Triggers

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Abstract: The present state of art in solar physics indicates that some key ingredients in explaining how the Sun re-generates its global magnetic field and its system of internal mass flows is missing. In fact, the experts do not agree which are the key processes that are involved. We show that the key processes include magnetic braking of solar *rotation*, magnetic reconnection and related *dynamo action*, and the gravitational and magnetic effects of *planets* on the Sun. In the usual framework, solar activity is thought to be generated in the convective zone or in its immediate surroundings. This standard view is contradicted by, for example, the fact that solar activity closely correlates with solar *luminosity* and *neutrino fluxes*. We found that the hypothesis that small changes in the solar interior cause proportionally much larger changes in the amplitude of the solar magnetic cycle can supply us the missing key of solar activity. In other words, to find all the key processes playing essential role at the origin of solar activity can be regarded as the Holy Grail in solar physics. Here we present the first comprehensive picture of solar activity based on results of detailed numerical calculations suitable to describe the key physical processes necessary to consider in the search for the origin of solar activity.

Keywords: Solar activity cycle, solar rotation, magnetic braking, dynamo action, irradiance changes, neutrino flux, thermal heating, nuclear instability, solar core.

SOLAR ACTIVITY AND ITS CONTEXT

Solar activity is the quasi-cyclic activity of the solar magnetic fields and mass flows. Not only the origin of solar activity and its energy source, but the key physical processes and the cause of the cyclic nature of solar activity are, at present, unknown. As one of the most eminent solar physicists, Eugene N. Parker (1977) formulated it;

One would expect from elementary physical principles that a massive, isolated, slowly rotating, self-gravitating, gently heated globe of gas like the Sun would be entirely placid, the epitome of celestial tranquility.

That the Sun is active, with continual emergence of magnetic field through the surface, continual eruption of gases, and wide-spread superheating, is a source of wonder – and a challenge – to the theoretical physicist.

The active phenomena on the Sun include relatively dark 'sunspots', 'active regions' emerging from below the photosphere, and sites of sudden energy release termed 'flares' (Figures **1** and **2**).

Figure 1: Solar flares arise due to the surfacing of a magnetic loop system. Time is measured downwards. First a small loop emerges from below the photosphere. As time proceeds (to the right), the loop develops into a loop system expanding upwards (modified from Bruzek, 1964).

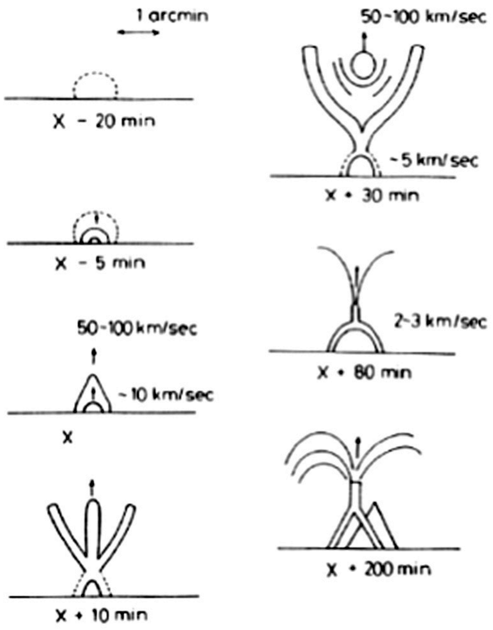

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Figure 2: Flares arise from surfacing high-speed subphotospheric hot spots when reaching the threshold of sonic boom around 10 km/sec. The arising sonic boom transforms the kinetic energy of the hot bubble into high-energy particle beams almost invisible for a terrestrial observer. These particle beams are injected from the photospheric region at time x into the magnetic loops above, which are bundles of field lines transported by the hot bubble from the solar interior. Flares arise from the interaction of the high-energy particle beam with the loop top (Grandpierre, 2010).

Importantly, the global magnetic field has a dipole nature. Activity increases and decreases in a cycle lasting for approximately 11 years. At solar maximum, sometimes 100-200 sunspots are visible. In contrast, in solar activity minimum, the number of sunspots decreases to nearly zero. Global and local forms of solar activity run closely parallel (Vidotto *et al.,* 2014).

Solar activity is strongly associated with magnetic fields (Hale, 1908; Babcock, 1961; Ridpath, 1997, p. 431; Ossendrijver & Hoyng, 2001), which are thought to arise from a *dynamo* acting within the Sun. The solar dynamo is the action whereby the kinetic energy of the hot, highly ionized gas of the mass flows in the solar interior is converted into the magnetic field that gives rise to solar activity.

One important source of energy of solar activity is the rotational energy of the Sun (Skumanich, 1972). Magnetic activity in Sun-like and low-mass stars causes X-ray coronal emission which is stronger for more rapidly rotating stars. The surface magnetic flux is determined solely by the star's rotation and is independent of other stellar parameters like the depth of the convective zone (Reiners *et al.,* 2014). The rotation of the Sun is decelerated by the magnetic field lines interconnecting it to the interplanetary space. This is the phenomenon of magnetic braking. While the Sun rotates with a period of roughly 27 days, the ionized plasma ejected from it and attached to its magnetic field will rotate slower and slower as it reaches much larger distances from the Sun. This effect of carrying mass far from the centre of the Sun and throwing it away leads to the spin-down of the Sun. Due to spinning-down, some part of the huge rotational energy will be transmitted into the solar interior and liberated in sporadic transient processes like earthquakes. The suddenly liberated rotational energy can heat small volumes to large temperatures that may form buoyant ‘hot bubbles’ moving upwards towards the solar surface (Grandpierre, 2010).

Besides magnetic field and rotation, *planetary effects play also a determining role in the origin of solar activity* (Grandpierre, 1996a). In our previous articles, we introduced the idea of a self-accelerating process of thermonuclear runaway in the solar core (Grandpierre, 1986, 1990, 1996a, 1996b). This idea has become powerful and inspired a variety of authors to work along similar lines (*e.g.* Wolff & Donovan, 2007; Wolff, 2009; Scafetta, 2012). In the present work, we identify the responsible physical mechanism amplifying planetary influences and transforming them into the observed forms of solar activity. In our previous work (Grandpierre 1996a) we pointed out that the three primarily important planetary constellations are that of the Jupiter (J), Venus (V) and Earth (E). The three periods are the ones when J and V are co-aligned with the Sun, and E is within 10 degrees, termed as JV,E; the other two are JE,V and EV,J. We have shown that the 11,1 years average period of solar activity arises as the average of these three planetary periods. Subsequently, we developed a suitable computer code describing concretely the effects of buoyancy, volume expansion and related cooling, dissipation due to viscosity and heat radiation, including all the important factors determining the time development of hot bubbles developing from a whole set of local heatings in the solar core (Grandpierre & Agoston, 2005; Grandpierre, 2010).

Remarkably, solar activity is also present in solar *luminosity changes*. The solar convection zone has a thermal relaxation time of 10^5 year (Foukal *et al.,* 2009). Therefore *it is unlikely that the 11-year period of the solar activity, if present in thermal effects as well, is caused by the processes of convective zone*. Willson & Hudson (1988, 1991) demonstrated that solar luminosity, corrected for sunspot effects, varies with the 11-year solar cycle. *The Sun radiates 0,1% more energy at solar maxima than in minima* (Willson & Hudson, 1991, Fig. 2). We point out here that *the corresponding energy changes are orders of magnitude higher than that of the activity-related changes in magnetic fields, rotation or planetary effects*. Therefore, we can consider the activity-related changes of solar irradiance as a basic fact to be explained by any theory of solar activity.

We propose to take into account these four facts, the role of magnetic fields, rotation, planets and irradiance as the basic facts for any future theory of solar activity.

THE DYNAMO PROBLEM

The *dynamo* is necessary to generate, destroy and regenerate the magnetic fields and the closely related forms of solar activity. Unfortunately, the present state of the dynamo theory is highly unsatisfactory. The disappearance of magnetic flux from the surface is still shrouded in mystery (Schrijver, 2001). Proper capture of important solar cycle elements – most notably the formation, emergence and surface decay sunspots and active regions – are certainly not forthcoming (Charbonneau, 2010). *The dynamo is one of the truly large mysteries in astrophysics* (Carpenter *et al.*, 2005). There is at present no model for a stellar dynamo that can be used to forecast the Sun's activity on the time scale of months to decades. There is not even a generally accepted approximate dynamo model. In fact, the experts do not agree *which are the key processes that are involved* (Carpenter *et al.*, 2005). *The standard view, which treats the solar cycle as a manifestation of the interaction between convection and magnetic fields, is shown to be misplaced* (Spruit, 2011).

A dynamo is simply a machine that converts mechanical energy into electro-magnetic energy. The flow of the plasma has to fulfill certain properties for the dynamo to work. *One need very complicated flows in order to generate any magnetic fields whatsoever* (Werne, 2014). Actually, the behavior of flows is determined by local physical conditions. These physical conditions change from point to point, from time to time and from cycle to cycle. Yet the dynamo with its complicated flows should work invariably within these changing conditions. The solar cycle has been working since billions of years. The system of conditions making the dynamo workable should remain invariant.

This is more demanding since the asymmetry of man-made dynamos is crucial for their success; in contrast, naturally occurring bodies such as planets, stars and galaxies do not have asymmetrical structures. If they are to act as dynamos, the asymmetry of their internal motions must, in some far from obvious way, compensate for their lack of structural asymmetry. *This astrophysical dynamo problem is far harder to conceive than the problem how to construct a man-made dynamo* (Proctor & Gilbert 1994, p. 5). Regular production of certain type of electromagnetic field from mechanical energies requires the construction of a machine. All known machines are man-made. Within the conceptual framework of physics, we think one cannot take it for granted that such a very complex machine can spontaneously 'emerge' in the solar interior.

The recent formulation of the second law of thermodynamics tells, "*All kinds of energy spontaneously spread out from where they are concentrated to where they are more dispersed, if they're not hindered from doing that*" (Leff, 1996; Lambert, 2005). In this light it is remarkable that due to solar activity, the global energy of the Sun becomes concentrated into relatively small volumes where solar activity is prominent. It is a matter of fact that in certain systems sometimes energy may become concentrated. For example, the kinetic energy of a braking car can be concentrated into the small volume where the wheels touch the ground and slip on it. The drag force can transform the kinetic energy of the car into heat. The heat becomes quickly dispersed, according to the second law of thermodynamics. In contrast, in the case of solar activity the heat due to the concentrated liberation of rotational energy may elicit a quasi-infinite cascade of phenomena maintaining and regenerating solar activity phenomena for billions of years. In our example, it is as if the braking car would use the heat liberated at dragging to drive the car. Such a harnessing of the frictional heat would require solving a formidable task in science and technology.

It is an important fact that *the diffusion of the magnetic energy proceeds extremely slowly, on the timescale of billion years* (Shore, 1992, p. 178). In contrast, observational facts show that during the actual course of a few years; the magnetic field, which is strong in the maximum phase of the solar activity cycle quickly disappears when the solar activity cycle enters its minimum phase, and the magnetic field almost completely vanishes, usually for one or two years. Only the mass flows in the solar interior transporting and modifying the magnetic fields can accelerate the changes of magnetic field in a rate billion times faster. Since the hot, highly ionized gas of the mass flows have extremely high conductivity, the magnetic field is “frozen“ into their matter. Such a fast, dynamical timescale can arise only by fluid motions transforming the magnetic fields moving with them. The mass flows make the solar cycle self-maintaining. Indeed, the solar cycle has been repeated during the lifetime of the Sun already – by order of magnitude – billion times. Comparing the characteristics of the activities of stars similar but younger than our Sun, Nandy & Martens (2007) found that there is no significant observed trend in the magnetic activity period versus age relationship – implying that the magnetic cycle period of a Sun-like star is independent of age. If so, the Sun has had almost half a billion activity cycles during its 5 billion years lifetime.

In the highly conducting gas of the deep solar interior magnetic diffusion and reconnection proceed extremely slowly, too slowly to explain the Sun's eleven-year cycle (Phillips, 1992, p. 70). The timescale t_{diff} of magnetic field’s changes is given by the relation $t_{\mathrm{diff}} = l^2/\eta$, where l is the characteristic size and η is the coefficient of diffusion. In the solar interior $\eta \sim 10^4$ cm^2 s^{-1} (Judge, 2014). Even for such a small spatial scale like $l = 10^7$ cm, the timescale of diffusion is $t_{\mathrm{diff}} \sim 10^{10}$ sec ~300 years, a very slow rate, especially when taking into account that the dissipation of magnetic energy occurs in different volumes at a different time, and that magnetic reconnection should destroy the field at practically all points in the solar interior. Additionally, *magnetic reconnection would require strong and very complicated compressive inflows of opposite direction at each site of magnetic reconnection*. In contrast, turbulent convection develops in a way avoiding direct collisions of oppositely directed massive mass flows. As observations tell, spots emerge first by exhibiting fragmented surface magnetic fields with mixed polarities. From this, clumps of opposite polarity then form and diverge without influence by convection. *This striking behavior of the magnetic fields at the development of sunspots is opposite of diffusion* (Spruit, 2011). Assuming effective magnetic reconnection at practically every point in the solar interior, as within the standard view of the dynamo arising from interaction with convection, is physically highly unrealistic.

A further fundamental problem is that, in order that the assumed 'turbulent convection' produces reconnection, such flows should carry with them *antiparallel field lines* and compress them by compressive inflows of opposite directions practically at each point in the solar interior. Parker (2009) points out that there is no way to account for the extremely high value a turbulent diffusivity necessary to accelerate the time scale of magnetic changes. While we know that astrophysical dynamos are at the heart of cosmic magnetic fields (Charbonneau, 2013), it is of fundamental importance to realize that actually, models of dynamo action based upon cyclonic turbulence cannot lie at the heart of the solar dynamo (Spruit, 2011). Simply put, how can small-scale turbulence cause the intense, clumped tubes of sunspot flux? How can order be produced from chaos (Judge, 2014)? Considering that the solar dynamo is driven by intense mass flows present in the solar interior, these mass flows must be fine tuned with the magnetic fields they interact in a special way to regenerate the activity cycle. If so, not only order, but also organization is a key factor of the solar cycle. But what is the source of this fine-tuning? *We still seem to be missing some key ingredients in explaining how the Sun and other stars re-generate their global magnetic fields* (Judge, 2014).

The Role of Rotation in the Origin of Solar Activity

In an inhomogeneous body penetrated by a magnetic field, rotational energy dissipation is generally manifested in intermittent local events. During the last $4.6*10^9$ years the solar core has spun down from a 50 times higher value at the zero-age main sequence (Charbonneau & MacGregor, 1992) $E_{rot,0} \approx 10^{45}$ ergs to the present one $E_{rot,present} \approx 2.4*10^{42}$ ergs (Allen, 1963, p. 161). From Fig. 2a of Charbonneau & MacGregor (1992) one can read that the present rate of solar spin-down corresponds to $(DE_{rot}/Dt)_{present} \approx 2*10^{34}$ ergs year^{-1}, or $6*10^{26}$ ergs s^{-1}. Assuming that the average period between spin-down events is, by order of magnitude, months or years, we would obtain a local heating event from the liberated rotational energy 10^{33}–10^{35} ergs.

Actually, the frequency of such spin-down events is not known. One idea can be to connect spin-down events with the formation of “hot spots” deep in the solar interior. Bai obtained that seven “hot spots” was observed during five solar cycles (Bai, 2003). From this we obtain that the rotational heating has a magnitude $DQ_0(rot) \approx 2*10^{35}$ ergs.

Planetary Influences in Solar Activity

Well before the magnetic field of sunspots became known, Rudolf Wolf, the Swiss astronomer pointed out that the conclusion seems to be inevitable, that the variations of spot-frequency depend on the influences of Venus, Earth, Jupiter, and Saturn (Wolf, 1849). Confirming Wolf’s finding, Wood (1972) presented a series of data showing that planetary tides and sunspot numbers run parallel in the whole period of data available, from 1750 to 1972. Even in the absence of any physical explanation, we can accept the planet-sunspot connection as an observational fact.

The basic fact that *planetary positions approximately match the sunspot cycle* (Wolf, 1959; Edmunds, 1882; Wood, 1972) was hard to take into account because the necessary theoretical framework was missing. The gravitational effect of planets in comparison to the gravitational force of the Sun to itself is in a ratio of $1:10^{-12}$. It is crucial to find a process amplifying the extremely small planetary effects in the solar interior. In this crucial point, recently a kind of breakthrough is happening. The physical basis amplifying the planetary influences in the solar core is found in the *local thermonuclear runaways developing hot ‘bubbles’ in the solar core capable to reach the surface within days* (Grandpierre, 1996a, 2010; Grandpierre & Agoston, 2005).

Planetary influences on solar activity attract more and more interest (Seymour, *et al.*, 1992; Tan & Cheng, 2013; Kashyap *et al.,* 2008; McCracken *et al.*, 2014; Liu & Wang, 2014; Scafetta, 2014). Hung (2007) had shown that among the 38 largest known flares at least twenty-five were observed to start when one or more tide-producing planets (Mercury, Venus, Earth, and Jupiter) were either nearly above the event positions (<10° longitude) or at the opposing side of the Sun. The planetary theory of solar variation is recently discussed in the works of the Special Issue in PRP: “Pattern in solar variability, their planetary origin and terrestrial impacts” (Mörner *et al.,* 2013; Mörner 2015, this volume). We reached the critical threshold having enough data to prove the existence of planetary effects. Methods of data processing develop fast. Analyzing the best datasets of solar irradiance Scafetta & Willson (2013) found *empirical evidence for planetary-induced* *forcing and modulation of solar activity*. They established that many planetary periods are present with amplitudes well above the limit of significance in the time series of the total solar irradiance.

We point out that the simultaneous key role of rotation, magnetic fields, and planetary positions in generating solar activity that changes solar luminosity in a rate of 0,1% is a strong indication that solar activity may originate from the core.

SOLAR ACTIVITY ORIGINATES FROM THE SOLAR CORE

It is of key importance in studying the origin of solar activity to consider from where is the necessary energy available. We demonstrated that in the solar atmosphere the energy of magnetic fields is unsuitable to give account for the violent solar flares (Grandpierre 1988). Considering the strong requirements of the extremely short timescale, extreme spatial compactness and extremely large magnitude of the energy liberated in large solar flares *our research led us to the novel conclusion that solar activity arises ultimately from the solar core* where the bulk of the energy of the Sun is produced (Grandpierre, 1986, 1988, 1990, 1996, 2004, 2010; Grandpierre & Agoston, 2005).

Solar luminosity is produced in nuclear reactions. The nuclear reactions occurring in the solar core produce not only energy but some elementary particles like neutrinos as well. These nuclear reactions can be monitored directly by measuring the solar neutrino flux. Neutrinos have the strange property to travel enormous distances in matter without being absorbed. In the last decades neutrino detectors have become powerful enough to detect them. It is of fundamental importance that the solar neutrino flux is found to vary with the activity cycle manifested on the solar surface (Haubold & Gerth, 1983, 1990; Haubold & Mathai, 1994; Gavryusev & Gavryuseva, 1994; Sakurai *et al.,* 2008; Khondekar *et al.*, 2012). *The strong correlation of the neutrino flux produced in the solar core with surface activity phenomena argues strongly that solar activity starts from the core*.

Considering the relations between such tantalizing problems of solar activity like the dynamo problem, the neutrino problem, the spin-down of the solar core, the flare-related chemical anomalies and the cycle variation of solar neutrino fluxes and solar luminosity we worked out a *pulsating-ejecting solar core model* (Grandpierre, 1996b). Accordingly, the variation of solar neutrino flux data within the solar activity cycle is found to be due to the *pulsating character of the nuclear energy generation inside the solar core* (Raychaudhuri, 1999). Ghosh & Raychaudhuri (2006) have found almost similar periods in the Rayleigh Power

Spectrum Analysis of the solar neutrino flux data, solar flares, sunspot data and solar proton data which indicates that the *solar activity cycle may be due to the variable character of nuclear energy generation inside the sun*. The results of Sturrock (2008a) are suggestive of *solar variability originating in the core from fluctuating and asymmetric nuclear burning*. The excitation of r modes in the radiative zone (*i.e.* the solar interior below the convective zone) may be due to a *velocity field originating in or related to the nuclear-burning core* (Sturrock, 2008b). The fact that the solar irradiance exhibits modulation identical to that of neutrinos leads to the *rather surprising conclusion that the irradiance is modulated by processes in the solar core* (Sturrock, 2009).

We find it of crucial importance that solar activity is so strong that it can increase the total luminosity of the Sun by 0,1 percent. Importantly, this activity-related luminosity change is already corrected for sunspot and facular effects (Willson & Hudson, 1998, Fig. 2; 1991, Fig. 2). It is useful to realize that 0,1% of solar luminosity is 2 x 10^{30} erg/sec. Considering that after nuclear and gravitational energy, rotation is the third largest source of energy of the Sun, *it is important to take into account that rotation can supply merely 3 x* 10^{26} *ergs/sec, which is almost ten thousand times smaller than present in the activity-related surplus of solar luminosity*, we obtained that the result that the surplus luminosity produced in solar maxima must have a nuclear energy source.

It is important to pay attention to another effect besides the cyclic luminosity variation. Already in 1975 it has been noticed that *during the flares significant temperature excesses develop in the photosphere* (Machado & Linsky, 1975). They wrote: "As long as 24 h before the flare, the active region begins to be heated by a presently unknown process which may be related to the sunspot energy deficit. As this process develops, the time scale for heating changes from hours to only minutes. Then what we call a thermal flare begins followed by the impulsive phenomenon." They found that thermal heating represents an amount of energy comparable to the total energy of flares, therefore it is an essential aspect of flares. Svestka (1976) pointed out that Machado & Linsky's above finding is a strong argument against all theories that place the flare origin above the chromosphere. Later on, Willson & Hudson (1991) emphasized that the total solar irradiance data show *two principal features of solar luminosity variation* on long timescales: the magnetic cycle itself *and the irradiance excess* of 1980, around solar maximum (*op.cit*, Fig. 2). *The irradiance excess suggests the existence of an unknown physical mechanism* other than the thermal diffusion model that explains luminosity deficits due to sunspots. In the face of these old observations, let us consider the new findings of Scafetta and Willson (Scafetta & Willson, 2013).

Their analysis has revealed a clear signature of the 1.09-year Earth-Jupiter conjunction cycle, in particular during solar cycle 23 maximum, suggesting that *the Jupiter side of the Sun is slightly brighter during solar maxima*. Again, the thermal heating is found to be an essential aspect of solar activity.

The problem is how to find a mechanism, which is energetic enough to supply the huge luminosity around 0,1% of total solar output yet at the same time fast enough to change on a timescale of 11 years. We found that this problem can be solved with the production of hot bubbles in the solar core in which thermonuclear runaway occurs. They are shown to be energetic enough (Grandpierre 2010) and fast enough to carry such huge energies from the core directly to the surface. These thermonuclear runaways represent a significant additional energy source of the Sun besides the quiet and balanced nuclear reactions taken into account until now.

There are other important facts indicating that solar activity has an aspect related to nuclear energy production at extreme temperatures. For example, the nitrogen enigma (Kerridge, 1989) states that the $^{15}N/^{14}N$ rate is enhanced by 50%, from a value 2.9×10^{-3} of 3×10^{9} years ago to a present day value of 4.4×10^{-3} (Kerridge *et al.,* 1991). It is just the opposite change of what the stellar evolution models predict. The production of significant amount of ^{15}N is possible only above 10^{8} - 10^{9}K. Considering that the highest temperature in the quiet solar core is only $1{,}6 \times 10^{7}$K, *the nitrogen enigma shows the presence of local explosive processes in the solar core,* i.e. the production of hot bubbles (Grandpierre, 1996, 2010). One can add that *observations show a whole series of flare-related chemical anomalies*. These anomalies are usually interpreted as apparent and due to selective effects in the solar atmosphere. In contrast, we presented arguments showing that *at least some of these flare-related chemical anomalies are intrinsic* (Grandpierre, 1996b). If so, they are further evidences for the presence of local thermonuclear runaways in the solar core.

The Problem of How to Initiate the Mass Flows in the Solar Core

The mass flows in the solar core can be initiated by *local heating* that produces *hot 'bubbles'* capable to move significant distances within the Sun. We carried out detailed numerical simulations of the movement of the hot bubbles from the solar core to the outer layers (Grandpierre & Agoston, 2005; Grandpierre, 2010). Our prediction of the existence of heat waves produced by the assumed hot bubbles has been confirmed by Ehrlich (2007; see also Clark, 2007). Our assumption that thermonuclear runaways can produce hot bubbles in the solar core in relation with the planetary tides has been confirmed (Hiremath, 2010; Haubold & Kumar, 2011; Scafetta, 2012) as well as the possibility of existence of hot bubbles within the solar core (Wolff & Donovan, 2007; Wolff, 2009). We predict that such dynamic processes involving thermonuclear runaways in the solar core will become detectable in the near future.

The next question is: how to initiate solar activity in the solar core? Our calculations showed that, in order to produce hot bubbles in the solar core capable of surviving dissipative effects and capable to reach the surface, *very large amplitude local heating of* $DQ_0 \approx 10^{31}$*-*10^{37} *ergs may be necessary in a volume not much larger than a kilometer* (Grandpierre & Agoston, 2005; Grandpierre, 2010). What kind of process can produce such strong local heating? The cyclic regeneration of the solar cycle requires the production of such hot bubbles to be regular. Therefore it cannot be a contingent event. But if hot bubbles cannot arise from spontaneous thermal fluctuations, in what process are they produced? As we indicated above, rotational energy liberation may offer 10^{33} –10^{35} ergs. In order to produce surface solar activity phenomena, in depending on the distance of the initial heating producing the hot bubbles from the solar centre, such an amount of initial energy may not be enough. The amplification mechanism we found (Grandpierre, 1996a) may be effective to produce a significant local heating from an initial heating if it is localized to a volume having a linear size between 1-10 km (Grandpierre & Agoston, 2005); the bubble do not survive the effects of dissipation if its initial size is lower than 1 km. By numerical calculations (Grandpierre, 2010), we obtained that 10^8 K is necessary for the nuclear time scale become dominant and produce thermonuclear runaways. Considering that the CNO cycle becomes important above 5 x 10^7 K, and the fact that the CNO cycle depends on a very high power of temperature, we find that thermonuclear runaways occur above 5 x 10^7 K. Therefore we obtain a lower limit to the initial heating for the thermonuclear runaways, DQ_0 (lower limit) = 10^{32} to 10^{35} ergs.

Let us now consider how the process capable to amplify the initial heating to hot bubbles works. In the quiet solar core, more than 98% of the energy production occurs by proton-proton cycle, converting hydrogen into helium. This process depends approximately on the fourth power of temperature (Böhm-Vitense, 1997, p. 155). Henry Norris Russell (1919) noted that the source of stellar energy must generate large quantities of heat per unit mass, but it must not be liable to *accelerate its own rate* as to end in an explosive catastrophe, for the stars in general appear to be very stable. Russell believed that the simple explanation may be found in the fact that a sphere of perfect gas, in equilibrium with its own gravitation, when heated, expands and its temperature falls. The same remark is found in Zel'dovich *et al.,* (1988, p. 124). They added that the stabilization occurs only when the perturbations are small, the star expands as a whole and its matter is not degenerated. Independently of them, we arrived at a similar idea with the difference that we found that a completely spherically symmetric heating of a star is not realistic. Instead, it is much more plausible to expect a local heating. In a local heating, a new phenomenon develops; the heated volume expands explosively, until it reached a critical size so that it can rise upwards by forming a hot bubble. Due to buoyant force, the hot bubble becomes accelerated upwards and can reach the surface within a few days under certain conditions.

For the sake of simplicity, let us consider the case when a small volume in the solar core is suddenly heated to a temperature double of its environment. Energy production by the proton-proton chain goes by the fourth power of temperature, therefore the energy production in this hot small volume will become accelerated at a rate 2 x 2 x 2 x 2 = 16. If so, the temperature will increase quickly, and the energy production will be accelerated in an even faster rate and so on. We arrived to a self-amplification process that we refer to as thermonuclear runaway (Grandpierre, 1986, 1990, 1996a, 1996b, 2000). The positive feedback works explosively until the size of the hot volume increases to such a rate that the buoyant force will accelerate the heated volume outwards. The rising hot bubbles expand, radiate heat and dissipate its energy surplus. Volume expansion, loss of heat and dissipation will cool down the hot bubble. We obtained a complete picture of all the effects influencing the speed of the rising hot bubble, energy production by nuclear reactions and energy loss processes with the help of concrete numerical calculations that required some years of intense efforts.

By detailed numerical calculations modeling physical conditions within the solar core and the hot bubbles formed there from a strong initial heating DQ_0, we found that a heating DQ_0, $\approx 10^{31}$-10^{37} ergs can be enough for a bubble to reach the outer convective zone. Our calculations had also shown that such a hot bubble arrives into the subphotospheric regions with $DQ_{final} \approx 10^{28}$-$10^{34}$ ergs, and with a high speed, up to 10 km s^{-1}, approaching the local sound speed (see Fig. 2). This means that the hot bubbles during their travel to the surface radiate much of their excess energy to their surroundings. One such bubble radiates 99,9% of its excess energy to the environment during its travel from the core to the surface. It is this excess energy produced by excess nuclear reaction by thermonuclear runaways at high temperatures that we propose to identify with the source of the flare-related irradiance excess.

On the Problem of Annihilating Magnetic Fields after Solar Maximum

and the Regeneration of the Solar Cycle

As we argued above, the standard picture about the dynamo working in or around the convective zone fails in some fundamental respects. It requires very complicated flows to accelerate magnetic diffusion and trigger magnetic reconnection. In view of the insurmountable difficulties of the standard solar dynamo, it seems appropriate to consider a basically new type of dynamo that starts to work in the core but exerts its effect in the whole of the solar interior.

In this paper we present a surprisingly simple and elegant picture that is capable to solve the major problems of the solar activity cycle. As Judge (2014) formulated, there are (at least) two major challenges in modern solar physics: (1) what causes the global regeneration of large-scale magnetic field with a period of ≈22 years, (2) why must the magnetic field appear most prominently in spots? Our simple picture presented below gives a simple and effective answer to both of these questions, explaining also the basic problem how the sunspots form from fibrils (Spruit, 2011).

Let us consider the example in which the north magnetic pole (N) of the global dipole field of the Sun is the upper one. The magnetic field lines of the global dipole field have a direction pointing from the north to the south, N-S. After the solar maximum, the hot bubbles traveling upwards from the core should carry with them a magnetic field having an opposite direction, S-N. In this way the hot bubbles carrying with themselves the S-N fields meet at their front the N-S field lines which they will compress, accelerating the process of reconnection, and reconnect, annihilating them. If the hot bubbles are produced with such oppositely directed field lines, on their way towards the surface they can annihilate most of the field lines they met.

If so, then the solar minimum naturally arises. Now if the production of S-N hot bubbles continues in the core, then the oppositely directed S-N global dipole field naturally arises, too. The southern pole, S will replace the upper northern pole, and polarity inversion occurs. The whole process can continue until the next solar maximum. But from this time onwards the hot bubbles in the solar core must be produced by opposite, N-S directed field lines, in order to decrease and annihilate the global dipole field again.

Keeping the mechanism of magnetic braking in mind, we found that the sudden concentration of a large amount of energy 10^{34}-10^{35} ergs to produce an initial heating suitable for the formation of a hot bubble can be produced by the sudden, earthquake-like event of solar spin-down. Certainly, the magnetic braking can trigger the sudden spin-down when reconnection occurs. Material flows compressing the magnetic field lines are important conditions of reconnection. Planetary influences can play a key role in triggering such material flows through tidal forces (Wood, 1972; Grandpierre, 1996a) or inertial effects (Charvatová, 1997, 2000, 2009). Moreover, we can keep in mind that planetary magnetospheres move within the magnetosphere of the Sun – the heliosphere – and therefore they can directly contribute in triggering magnetic reconnection (Scafetta & Willson, 2013). Since reconnection by its very nature occurs in a point-like volume, this mechanism offers a natural way to concentrate the rotational energy into a point-like small volume. If so, the temperature in this point-like small volume will be very high, and the conditions for the generation of a thermonuclear runaway will be present and the positive feedback will lead to a strong amplification. Therefore the hot bubble can grow explosively. The initial heating arisen from rotational energy will be completed by the additional energy produced in the thermonuclear runaway. We found that our picture is able to take into account the basic facts that solar spin-down, magnetic reconnection, and planets all play a crucial role at the origin of solar activity.

But how can the magnetic fields of the hot bubbles be produced, and how does their periodic polarity inversion take place?

THE PRODUCTION OF THE MAGNETIC FIELD OF HOT BUBBLES

First of all we have to take into account that the temperature of the hot bubbles can reach 50-100 million degrees (Grandpierre, 2010). Their strong initial heating arises from the sudden liberation of rotational energy elicited by the interplay of magnetic fields and planetary influences. As a result of magnetic braking and planetary effects, the magnetic field of different interconnected regions can reconnect. For example, the field lines interconnecting outer and inner regions will be sheared by magnetic breaking. The shear of magnetic field lines makes them longer. This effect acts to produce electric currents. These currents produce secondary magnetic fields that may serve as ingredients for the reconnection when pushed together by inertial motions, tidal flows or by interconnecting with the field lines related to planetary magnetospheres. Once the magnetic reconnection occurs, it becomes possible to form local plasmoids, closed islands of strong magnetic fields in case of suitable conditions. At the same time, the strong local heating produces hot bubbles. As in the case of Benard convection, at the formation of convective cells heated from below, the hot convective cells *spontaneously* form *internal circulations*. The formation of these internal circulations of the hot bubbles may contribute to the formation of plasmoids enveloping the hot bubbles in case of suitable conditions. Once these conditions are present, the hot bubbles may be generated with strong magnetic fields carrying a plasmoid enveloping them.

What is the strength of the magnetic field in the solar core? At the surface of the Sun the strength of the global dipole field is around 1 Gauss, roughly the double of the field at the surface of the Earth. In the solar core, the field can be much stronger, around 1000 Gauss (Gough & McIntyre, 1998) or larger (Hiremath, 2005). Fridland & Gruzinov (2004) suggested that a field of 2 x 10^6 Gauss may survive until today in the solar core. Considering our results showing that solar activity is originated from the core, we found this suggestion highly problematic. If a fossil field would supply the field for the next cycles, than it would be quickly exhausted, considering that each cycle consumes with an activity-related luminosity of 2 x 10^{30} ergs/sec within the 11 years – which is roughly 3,5 x 10^8 sec – a total energy 7 x 10^{38} ergs. Such a rate of solar activity would exhaust in the inner solar core even a field as strong as 10^6 Gauss within a few cycles. In contrast, we know that the number of solar cycles already happened is roughly half billion. We obtained a result that no fossil field can be present within the solar core. This means that the whole field present in solar activity must be produced from scratch from cycle to cycle. What is more, *not only the magnetic field should be produced from scratch in each cycle but the dynamo generating the field as well.*

The external physical influences arising from magnetic braking of the solar rotation or planetary influences prevail independently from the direction and strength of magnetic fields present in the solar interior. Therefore, one cannot expect a fine tuning between the planetary effects, solar spin-down and the magnetic field that should build up the plasmoid of the hot bubble. Nevertheless, they may supply the necessary, but not sufficient, conditions to produce the plasmoid's dynamo. The plasmoid enveloping the hot bubble may contribute to maintain the hot bubble's integrity during its travel. Moreover, the plasmoid envelope may contribute to the surfacing of the hot bubble by magnetic buoyancy, the effect arising from magnetic pressure in decreasing the density of the material within the hot bubble. The origin of polarity inversion with an average period of 22 years can be related to planetary periods like the 22-year cycle of solar revolution round the solar mass center (Liu & Wang, 2014).

Let me summarize the results obtained:
1. Solar activity is triggered by the interplay of rotation, magnetic field, planetary

effects that together co-operate in generating thermonuclear runaways in the solar core.
2. They interact not only as triggers of thermonuclear runaways but as key factors generating the plasmoid enveloping the hot bubble in a manner suitable to generate and re-generate the solar cycle.
3. The solar dynamo is much more complex than the man-made one. Yet the man-made dynamo is a machine. This aspect of the dynamo requires an approach to solar activity on a conceptually wider basis than usually is the case in solar physics. We found a surprisingly simple solution for the solar dynamo problem. Once the plasmoids of hot bubbles in the solar core are produced with an opposite polarity in every quasi-22-year period, the hot bubbles moving upwards solve the main problem to destroy and re-generate the field as well as all the phenomena of solar activity.
4. The Sun maintains its activity by lawfully circumventing the second law of thermodynamics, harnessing the arising physical conditions.
5. Within the continuously varying physical conditions the Sun is effective in realizing its invariant and subtle patterns of activity, including the deep-seated local dynamo in the solar core producing the plasmoids of the hot bubbles.
6. The liberation of rotational energy, magnetic reconnection, and planetary influences are all necessary, but not sufficient, conditions of solar activity.
7. The dynamo itself is annihilated and re-generated in each cycle.

CRITICAL REMARKS ON THE PHYSICS OF SOLAR ACTIVITY

We have to point out that the origin of solar activity is a question related to until now unrecognized, deep conceptual problems. First of all, we cannot take it for granted, *a priori*, that the Sun can have only physical aspects. The more so, because the solar dynamo is more complex than its man-made, simpler version, which is already a machine. Machines are created by a system of initial conditions that together represent the design principle of the machine capable to produce a prescribed output by its functioning. This aspect of the dynamo is the one related to the continuous generation and re-generation of solar activity. We do not think that the cyclic re-generation of solar activity can be reached without a kind of *control* of the initial conditions. If so, solar activity is a deeper problem than it is widely believed.

McCracken *et al.* (2014) claimed that the Jovian planets provide the clock, regulating the period of solar activity. They also noted that the direct effect of the planets on the Sun is too weak and so a physics-based internal amplification mechanism remains to be identified. We found that the 11,2 year period is given not by the Jovian planets but by the positions of Jupiter, Earth and Venus (Grandpierre, 1996a). In this chapter we have developed a physics-based picture supplied with an already published numerical model (Grandpierre, 2010) of the crucial processes that calculates the internal amplification mechanism in detail.

It is already recognized that the motion of the Sun relatively to the barycentre of the Solar System exerts inertial forces to the solar interior (José, 1965; Charvátová, 1997, 2009; Cioncoa & Compagnucci, 2012). Charvátová (2009) and Cioncoa & Compagnucci (2012) has called attention to barycentric dynamics and the Sun's capability of storing hypothetical reservoirs of potential energy that could be released by internal flows and might be related to the solar cycle. Wolff & Patrone (2010) argued that planetary gravitational forcing could cause a mass flow inside the Sun that could carry fresh hydrogen fuel to deeper levels including the solar core consequently increasing the solar nuclear fusion rate. Unfortunately, the crucial aspect of how to initiate the mass flows, has remained unexplored. But exactly this aspect is what we studied in detail by numerical simulations showing that such small effects cannot elicite mass flows (Grandpierre 2010).

On the basis of the idea that the Sun amplifies the planetary effects (Grandpierre, 1990, 1996a), Scafetta (2012) proposed that the gravitational energy released by the planetary tides to the Sun may trigger slight nuclear fusion rate variations by enhancing solar plasma mixing. Based on our detailed numerical calculations, we can realize that such a slight modification of nuclear energy production cannot produce the observed surface activity phenomena in a way that they arise from the solar core. We estimated that the gravitational energy released by planetary tides is smaller than 10^{22} ergs s^{-1} (Grandpierre, 2004). Such a small heating does not initiate mass flow but dissipates in the form of heat waves (Grandpierre & Agoston, 2005). Moreover, even for much larger energy release, we found that if it occurs in a volume much larger than 1 km^3, the arising amount of heating is too small to produce a hot bubble capable of reaching the solar surface (Grandpierre, 2010). We have to point out that according to our concrete numerical simulations solving the corresponding partial differential equations, no flows in the solar interior can reach the surface and contribute to solar activity which do not produce sudden, strong and local heatings reaching an amplitude larger than 10^{31}–10^{37} ergs in a volume of ~10^{27} cm^3 (Grandpierre & Agoston, 2005; Grandpierre, 2010). We found that the amplitude of the necessary initial heating DQ_0 is higher for hot bubbles produced closer to the solar centre. DQ_0 ~10^{37} ergs is necessary for a bubble to be produced around 0,1 solar radius, and DQ_0 ~10^{31} ergs is necessary for a bubble produced around 0,7 solar radius. In the latter case the density and temperature of the bubble is far from being suitable to produce thermonuclear runaways.

We consider that all the above approaches miss to take into account the fundamental fact that solar activity is a phenomenon, in which both rotation, magnetic fields, planetary positions and thermonuclear runaways play a key role. Moreover, they fail to take into account the relevant physical processes and calculate them in their time evolution. In contrast, our approach is suitable to consider all these fundamental facts. At the same time, it is the only one which follows by numerical calculation the temporal evolution of the hot bubbles from their formation in the solar core until they generate the sunspots, flares and related phenomena at the solar surface (Grandpierre & Agoston, 2005; Grandpierre, 2010).

OUTLOOK

We found that solar activity presents a really big challenge for physicists because of a surprisingly large number of surprisingly deep reasons. The solar dynamo generating and re-generating the highly complex magnetic field require the fine tuning of the time development of mass flows to the rotation, magnetic field and planetary influences and the solar structure in a way suitable to re-generate the solar cycle. Moreover, the dynamo itself is destroyed and re-generated from cycle to cycle. The regular and complete re-generation of the dynamo from scratch presents a deep problem requiring wider than usual conceptual frameworks. At the same time, solar activity crucially depends on rotation and planetary influences. In this respect, it is reasonable to re-think the conceptual framework in which solar activity is usually approached. We found serious indications that solar activity is related to deep and intriguing issues that are related to some of the biggest unsolved problems in philosophy, namely, the origin and nature of self-initiated activity (Moya, 1990, p. 2-3). Established methods well performing within narrower contexts are not guaranteed to offer solutions within new, wider perspectives. At the same time, such questions can be regarded as more and more timely. The search to explore the origin of solar activity requires questions that did not even show up until now.

CONFLICT OF INTEREST

None declared

ACKNOWLEDGEMENT

I thank to Dr. Nils-Axel Mörner for inviting me to write this paper, for his useful suggestions and to Dr. Richard C. Willson for useful information about solar irradiation.

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