



# The Venus–Earth–Jupiter spin–orbit coupling model

I. R. G. Wilson

The Liverpool Plains Daytime Astronomy Centre, Gunnedah, Australia

Correspondence to: I. R. G. Wilson (irgeo8@bigpond.com)

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**Abstract.** A Venus–Earth–Jupiter spin–orbit coupling model is constructed from a combination of the Venus–Earth–Jupiter tidal-torquing model and the gear effect. The new model produces net tangential torques that act upon the outer convective layers of the Sun with periodicities that match many of the long-term cycles that are found in the  $^{10}\text{Be}$  and  $^{14}\text{C}$  proxy records of solar activity.

## 1 Introduction

The use of periodicities to investigate the underlying physical relationship between two variables can be fraught with danger, especially if reasonable due care is not applied. Any use of this technique must be based upon the following premise: if two variables exhibit common periodicities, it does not necessarily prove that there is a unique physical connection between the two. This is the dictum saying that a correlation does not necessarily imply causation.

However, there are cases where the correlation between two variables is so compelling that it makes it worthwhile to investigate the possibility that there may be an underlying physical connection between the two. One such case is the match between the long-term periodicities observed in the level of the Sun's magnetic activity and the periodicities observed in the relative motion of the planets.

Jose (1965) showed that the Sun's motion around the centre-of-mass of the solar system (CMSS) is determined by the relative orbital positions of the Jovian planets, primarily those of Jupiter and Saturn. He also showed that the time rate of change of the Sun's angular momentum about the instantaneous centre of curvature of the Sun's motion around the CMSS ( $= dP/dT$ ), or torque, varies in a quasi-sinusoidal manner, with a period that is comparable to the 22 yr Hale cycle of the solar sunspot number (SSN).

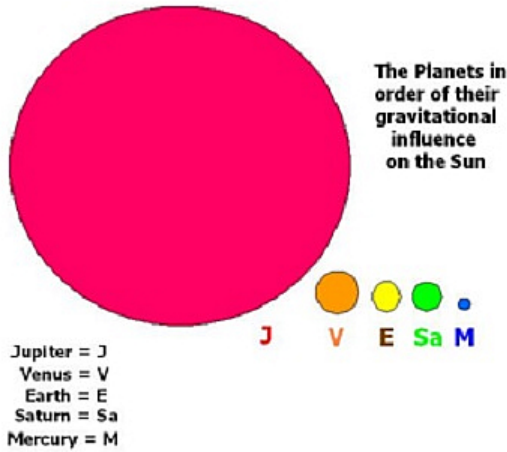
Jose (1965) found that the temporal agreement between variations in  $dP/dT$  and the SSN were so compelling that it strongly hinted that there was a physical connection between the planetary induced torques acting upon the Sun and sunspot activity. However, Jose was unable to give a

physically plausible explanation as to how this connection might work.

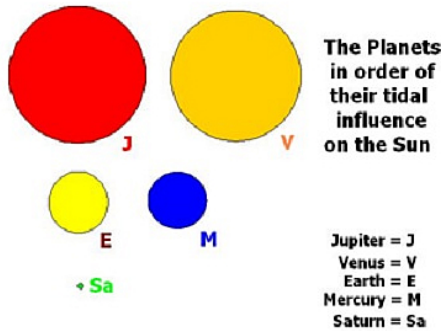
Following Jose's original work, there were several further attempts to link the Sun's motion around the CMSS with long-term variations in solar activity (Landscheidt, 1981, 1999; Fairbridge and Shirley, 1987; Chárvtova, 1988, 1990, 2000; Zaqarashvili, 1997; Javaraiah and Gokhale, 1995; Javaraiah, 2003; Juckett, 2000). However, each of these attempts was dismissed by Shirley (2006), based upon the argument that differential forces within the Sun cannot be produced by the Sun's motion around the CMSS (hereafter referred to as the solar inertial motion or SIM), since the Sun is in a state of free-fall. Shirley (2006) claimed that the only differential forces that could be generated within the Sun by the planets were those associated with their extremely weak tidal forces.

De Jaeger and Versteegh (2005) went one step further, claiming that the observed accelerations of plasma in the base of the convective layers of the Sun, where the solar dynamo is thought to originate, were 1000 times greater than those induced by the planetary tides. This makes it very difficult to argue that planetary tidal forces can play a significant role in influencing the solar dynamo.

Despite these strong counterarguments, Wilson et al. (2008) found further observational evidence that there was a link between the SIM and long-term changes in SSN. They showed that there was a correlation between the Sun's equatorial rotation rate and its motion about the CMSS (i.e. a form of spin–orbit coupling) that was associated with long-term changes in the SSN. However, Wilson et al. (2008)



**Figure 1.** The relative gravitational influence of the planets upon the Sun. NB: all comparisons should be made using the circle’s diameters and not their areas.



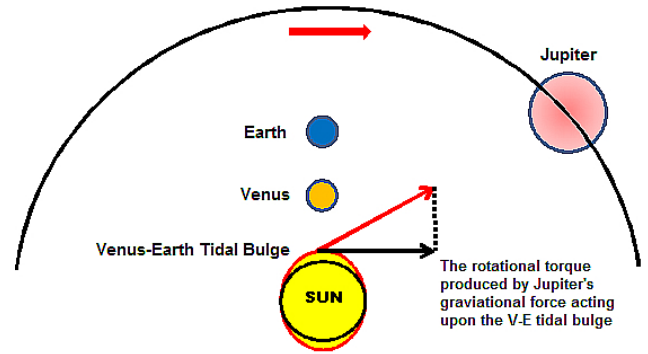
**Figure 2.** The relative tidal influence of the planets upon the Sun. NB: all comparisons should be made using the circle’s diameters and not their areas.

could not provide a physically plausible explanation for the observed spin–orbit coupling.

At about the same time, Hung (2007) and Wilson (2011) advanced the idea that there was a connection between the tides induced in the surface layers of the Sun by periodic alignments of Jupiter, Venus and the Earth (VEJ) and long-term changes in SSN. NB: this idea was first proposed by Bollinger (1952) and Desmoulins (1989) and then further developed by others in the non-peer reviewed literature (see Acknowledgements).

Claims by Hung (2007) and Wilson (2011) were based upon the fact that there are 11.07 and 22.14 yr periodicities in the planetary tides induced in the surface layers of the Sun by Jupiter, Venus and the Earth and that these periodicities closely matched the observed Schwabe and Hale SSN cycles. However, despite the suggestive nature of the matching periods, the problem still remained that the VEJ models relied on tidal forces that were orders of magnitude too weak

**VEJ Tidal-Torquing Model**



**Figure 3.** An over-view of the VEJ tidal-torquing model – further details in the text.

to produce any significant bulk motions at the base of the convective layer of the Sun (Callebaut et al., 2012).

One way to overcome the inadequacies of the planetary tidal models was to postulate that the layers of plasma at the base of the convective layer of the Sun (i.e. near the tachocline) were somehow aspherical, allowing the gravitational forces of the planets (primarily that of Jupiter) to apply torques that were tangential to the solar surface.

Two types of models have been proposed along these lines. The first is the model by Abreu et al. (2012) that assumes there is an intrinsically non-spherical tachocline at the base of the Sun’s convective zone. The Abreu et al. (2012) model can successfully reproduce many of periodicities that are observed in the <sup>10</sup>Be and <sup>14</sup>C proxy records of solar activity over the last 9400 yr. The second type of model is the Venus–Earth–Jupiter tidal-torquing model presented and discussed here.

**2 The Venus–Earth–Jupiter tidal-torquing model**

The Venus–Earth–Jupiter (VEJ) tidal-torquing model is based on the idea that the planet that applies the dominant gravitational force upon the outer convective layers of the Sun is Jupiter (Fig. 1), and after Jupiter, the planets that apply the dominant tidal forces upon the outer convective layers of the Sun are Venus and the Earth (Fig. 2).

Periodic alignments of Venus and the Earth on the same or opposite sides of the Sun, once every 0.7993 sidereal Earth years, produces temporary tidal bulges on the opposite sides of the Sun’s surface (Fig. 3 – red ellipse). Whenever these temporary tidal bulges occur, Jupiter’s gravitational force tugs upon the tidally induced asymmetries and either slows down or speeds-up the rotation rate of plasma near the base of the convective layers of the Sun.

The VEJ tidal-torquing model proposes that it is the variations in the rotation rate of the plasma in Sun’s lower

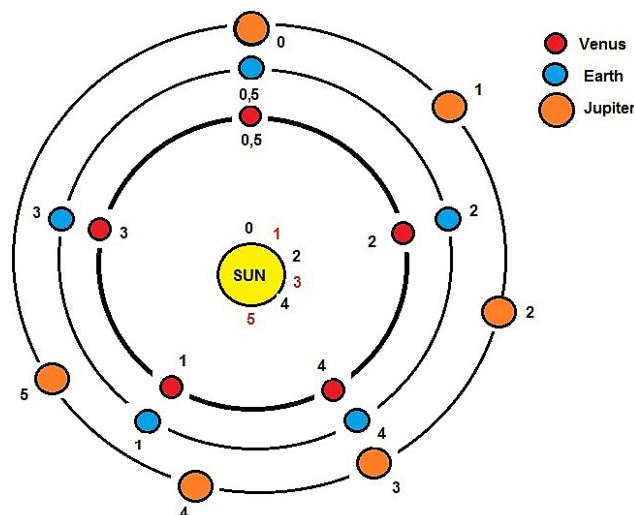
convective layer, produced by the torque applied by Jupiter upon the periodic Venus–Earth (VE) tidal bulges that modulate the Babcock–Leighton solar dynamo. Hence, the model asserts that it is the modulating effects of the planetary tidal-torquing that are primarily responsible for the observed long-term changes in the overall level of solar activity.

It is important to note that tidal bulges will be induced in the surface layers of the Sun when Venus and the Earth are aligned on the same side of the Sun (inferior conjunction), as well as when Venus and the Earth are aligned on opposite sides of the Sun (superior conjunction). This means that whenever the gravitational force of Jupiter increases/decreases the tangential rotation rate of the surface layer of the Sun at inferior conjunctions of the Earth and Venus, there will be a decrease/increase the tangential rotation rates by almost the same amount at the subsequent superior conjunction.

Intuitively, one might expect that the tangential torques of Jupiter at adjacent inferior and superior conjunctions should cancel each other out. However, this is not the case because of a peculiar property of the timing and positions of Venus–Earth alignments. Each inferior conjunction of the Earth and Venus (i.e. VE alignment) is separated from the previous one by the Venus–Earth synodic period (i.e. 1.5987 yr). This means that, on average, the Earth–Venus–Sun line moves by 144.482 degrees in the retrograde direction, once every VE alignment. Hence, the Earth–Venus–Sun line returns to almost the same orientation with respect to the stars after five VE alignments of almost exactly eight Earth (sidereal) years (actually 7.9933 yr). Thus, the position of the VE alignments trace out a five pointed star or pentagram once every 7.9933 yr that falls short of completing one full orbit of the Sun with respect to the stars by  $(360 - (360 \times (7.9933 - 7.0000))) = 2.412$  degrees.

In essence, the relative fixed orbital longitudes of the VE alignments means that, if we add together the tangential torque produced by Jupiter at one inferior conjunction, with the tangential torque produced by Jupiter at the subsequent superior conjunction, the net tangential torque is in a prograde/retrograde direction if the torque at the inferior conjunction is prograde/retrograde.

What makes this simple tidal-torquing model most intriguing is the time period over which the Jupiter’s gravitational force speeds up and slows down the rotation rate of the Sun’s outer layers. Figure 4 shows Jupiter, Earth and Venus initially aligned on the same side of the Sun (position 0). In this configuration, Jupiter does not apply any tangential torque upon the tidal bulges (the position of the near-side bulge is shown by the black 0 just above the Sun’s surface). Each of the planets, 1.5987 yr later, moves to their respective position 1s. At this time, Jupiter has moved 13.00° ahead of the far-side tidal bulge (marked by the red 1 just above the Sun’s surface) and the component of its gravitational force that is tangential to the Sun’s surface tugs on the tidal bulges, slightly increasing the rotation rate of the Sun’s outer layers.



**Figure 4.** The VEJ tidal-torquing model produces a net increase/decrease in the rotation rate of the outer layers of the Sun that lasts for 11.07 yr, followed by a net decrease/increase in the rate of rotation of the outer layers of the Sun that lasts for another 11.07 yr. Further description in the text.

After a second 1.5987 yr, each of the planets moves to their respective position 2s. Now, Jupiter has moved 26.00° ahead of the near-side tidal bulge (marked by the black 2 just above the Sun’s surface), increasing Sun’s rotation rate by roughly twice the amount that occurred at the last alignment. This pattern continues with Jupiter getting 13.00° further ahead of the nearest tidal bulge, every 1.5987 yr. Eventually, Jupiter will get 90° ahead of the closest tidal bulge and it will no longer exert a net torque on these bulges that is tangential to the Sun’s surface and so it will stop increasing the Sun’s rotation rate.

Interestingly, Jupiter’s movement of 13.00° per 1.5987 yr with respect to closest tidal bulge means that Jupiter will get 90° ahead of the closest tidal bulge in 11.07 yr. This is almost the same amount of time as to average length of the Schwabe sunspot cycle ( $11.1 \pm 1.2$  yr, Wilson, 2011). In addition, for the next 11.07 yr, Jupiter will start to lag behind the closest tidal bulge by 13.00° every 1.5987 yr, and so its gravitational force will pull on the tidal bulges in such a way as to slow down the rotation rate of the outer convective layers of the Sun. Hence, the basic unit of change in the Sun’s rotation rate (i.e. an increase followed by a decrease in rotation rate) is  $2 \times 11.07 \text{ yr} = 22.14 \text{ yr}$ . This is essentially equal to the mean length of the Hale magnetic sunspot cycle of the Sun, which is  $22.1 \pm 2.0 \text{ yr}$  (Wilson, 2011).

Figure 5 shows the observed variation in the SSN between 1748 and 2008 (top curve – labelled SSN). Also shown in this figure is the variation of a parameter that is directly proportional to the net tangential torque that is applied by Jupiter to the periodic VE tidal bulges, according to the VEJ tidal-torquing model (bottom curve – labelled Torque, shown in

arbitrary units and offset by  $-50$  for comparison purposes). In order to further help with comparisons, a fifth-order binomial filter has been applied to the torque data to produce the smooth curve that is superimposed on the torque curve (Horizons On-Line Ephemeris System, 2008).

The net tangential torque calculated from the model exhibits a number of properties that closely match the observed variations that are seen in the Sun's long-term magnetic activity:

- It naturally produces a net increase/decrease in the rate of rotation of the outer layers of the Sun that lasts for 11.07 yr (i.e. equivalent to the Schwabe cycle), followed by a net decrease/increase in the rate of rotation of the outer layers of the Sun that also lasts for 11.07 yr.
- Hence, the net torque of Jupiter acting on the VE tidal bulge has a natural 22.14 yr periodicity that closely matches the observed period (and phase) of the 22.1 yr Hale (magnetic) cycle of solar activity.
- If one considers the torque of Jupiter upon the VE tidal bulge at each separate inferior and superior conjunction of Venus and Earth (*rather than their consecutive sum = net torque*), the actual magnitude of Jupiter's torque is greatest at the times that are at or near solar minimum. Even though Jupiter's torque is a maximum at these times, the consecutive torques at the inferior and superior conjunctions of Venus and the Earth almost exactly cancel each other out.
- In all but two cases between 1750 and 2013, the time for solar minimum is tightly synchronized with the times when Jupiter's *net torque* (acting on the VE tidal bulge) is zero (NB: this is the time when the net torque changes direction with respect the Sun's rotation axis, R. Martin, personal communication, 2013).
- On these two occasions where the synchronization was disrupted (i.e. the minima prior to the onset of cycle 4 (1784.7) and cycle 23 (1996.5), the timing of the sunspot minimum quickly re-synchronizes with the timing of the minimum change in Jupiter's tangential force acting upon Venus–Earth tidal bulge. Interestingly, the minimum prior to cycle 4 (1784.7) marks the onset of the Dalton Minimum and minimum prior to cycle 23 (1996.5) marks the onset of the upcoming Landscheidt Minimum.
- Remarkably, if the minimum between solar cycles 24 and 25 occurs in  $2021 \pm 2$  yr, it will indicate a re-synchronization of the solar minima with a VEJ cycle length of  $11.07 \pm 0.05$  yr over a 410 yr period.
- The equatorial convective layers of the Sun are sped-up during ODD numbered solar cycles and slowed-down during EVEN numbered solar cycles, thus providing a logical explanation for the Gnevyshev–Ohl (G–O)

rule for the solar sunspot cycle (Gnevyshev and Ohl, 1948).

(NB: since the VEJ tidal-torquing model has a natural aliasing set by the physical alignments of Venus and the Earth, simple auto-regression analysis of the smoothed torque curve in Fig. 5 indicates that the (short-term) repetition cycle is 22.38 yr (= 7 VE alignments) rather than 22.14 yr. Essentially, what this means is that while the tangential torques affecting the convective layers of the Sun are being applied over a 22.14 yr repetition cycle, any external mechanism that uses the VE alignments to interact with the tidal-torquing mechanism, will attempt to do so over periodic cycles that are 22.38 yr long).

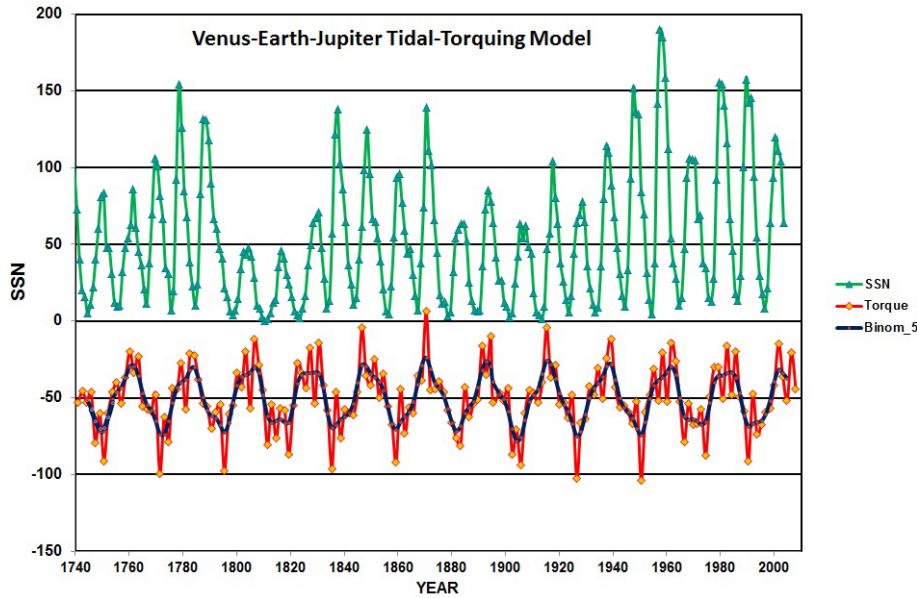
Figure 6 shows the smoothed torque curve from Fig. 5, re-plotted to highlight its long-term modulation (Horizons On-Line Ephemeris System, 2008). Superimposed on the torque are two sinusoidal envelopes with periods of 166.0 yr. In order to understand why the torque is modulated by this long-term period, we need to understand the main factors that influence long-term changes in the torque that Jupiter applies to the VE tidal bulges. These factors are the 3.3-degree tilt in the heliocentric latitude of Venus' orbit and the mean distance of Jupiter from the Sun.

Figure 7 (from Wilson, 2011) shows that the variations in the heliocentric latitude of Venus essentially mimics the variations in the mean distance of Jupiter from the Sun, provided these variables are measured at the times when Jupiter aligns with either the inferior or superior conjunctions of Venus and the Earth. What this indicates is that the long-term net tangential torque should be weakest when Venus is at its greatest positive (most northerly) heliocentric latitude, and Jupiter is at its greatest distance from the Sun ( $\approx 5.44$  A.U.). Figure 7 shows that this condition reoccurs roughly once every 166 yr and that they correspond in time with periods of low solar activity known as Grand Solar Minimum. The one exception to this rule since 1000 AD is a period of weak planetary tidal force that peaks near 1150 AD spanning the first half of the Medieval Maximum from 1090–1180 AD. The reason for this discrepancy is unknown, although it could be explained if there is an additional countervailing factor present during this period that was working against the planetary tidal effects.

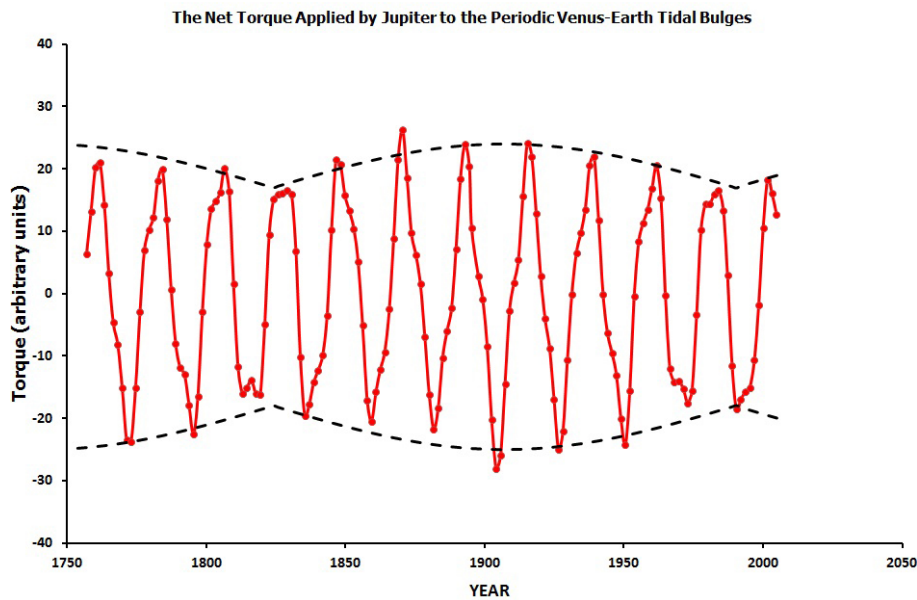
So, in summary, the Venus–Earth–Jupiter tidal-torquing model naturally produces 11.07 and 22.14 yr periodicities in the net tangential torque that Jupiter applies to the base of the convective layer of the Sun. These periodicities closely match the 11.1 yr Schwabe and the 22.1 yr Hale solar activity cycles. In addition, the model gives a natural explanation for the G–O rule for SSN and it provides a plausible physical explanation for the average spacing in time between recent Grand Solar Minima in solar activity of approximately 166 yr.

Despite all of these successes, the model is unable to easily produce the known periodicities that are associated with the





**Figure 5.** The observed variation in the SSN (green) between 1748 and 2008. The torque curve (red) represents a parameter that is directly proportional to the net tangential torque that is applied by Jupiter to the periodic VE tidal bulges, according to the VEJ tidal-torquing model (bottom curve shown in arbitrary units and offset by  $-50$  for comparison purposes). A fifth-order binomial filter has been applied to the torque data to produce the smooth curve (black) that is superimposed on the torque curve.



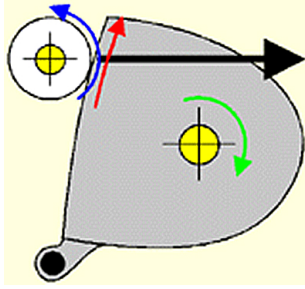
**Figure 6.** The smoothed torque curve from Fig. 5, replotted to highlight its long-term modulation. Superimposed on the torque are two sinusoidal envelopes (dashed) with periods of 166.0 yr.

$^{10}\text{Be}$  and  $^{14}\text{C}$  proxy observations of the long-term variations in the level of solar activity (column 1 of Table 1). In order to accomplish this we must combine the VEJ tidal-torquing model with the gear effect to produce a new model called the VEJ spin–orbit coupling model.

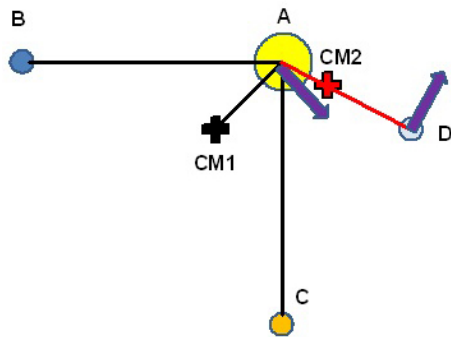
### 3 The Venus–Earth–Jupiter spin–orbit coupling model

#### 3.1 The gear effect

The gear effect is the term used in golf to describe the action of a club head upon a golf ball that causes it to either slice



**Figure 7a.** An explanation as to how the gear effect can be used either to slice or to hook a golf ball off a tee. If the golf ball hits the (curved) face of the club off-centre, it applies a force (horizontal black arrow) to the club, which induces clockwise rotation of the club head (green arrow) around its centre-of-mass (bottom right yellow circle with cross-hairs). The resultant rotation of the face of the club head (red arrow) applies a side-ways force to the golf ball at the point of contact, producing an anti-clockwise rotation (blue arrow) of the golf ball.



**Figure 7b.** A more specific example that removes many of ambiguities of the golf club analogy. In this figure, the head of the golf club is replaced by a structure that consists of three spheres A, B, and C, that are held together by rigid bars. The ABC structure is free to rotate in the plane of the page around a centre-of-mass (CM1). CM1 is located at a fixed distance from the sphere A, as well as a fixed point on the page. Similarly, the golf ball is replaced by a structure that consists of two spheres A and D. These spheres are held together by a rigid bar, as shown. The AD structure is free to rotate in the plane of the page around a centre-of-mass (CM2). CM2 is located a fixed distance from the sphere A, however it is able to move freely in the plane of the page. For more detail about how this analogy is used to describe the gear effect please refer to the text.

or hook. The gear effect occurs whenever two bodies impact at an angle or impact with misaligned centres-of-mass (i.e. the point of impact between them does not lie along the line connecting the two bodies’ centres-of-mass).

Figure 7a shows how the gear effect can be used to either slice or hook a golf ball off a tee. If the golf ball hits the (curved) face of the club off-centre, it applies a force (horizontal black arrow) to the club, which induces clockwise rotation of the club head (green arrow) around its centre-of-mass (bottom right yellow circle with cross-hairs). The re-

**Table 1.** Periodic variations in the level of solar activity – longer the Gleissberg cycle.

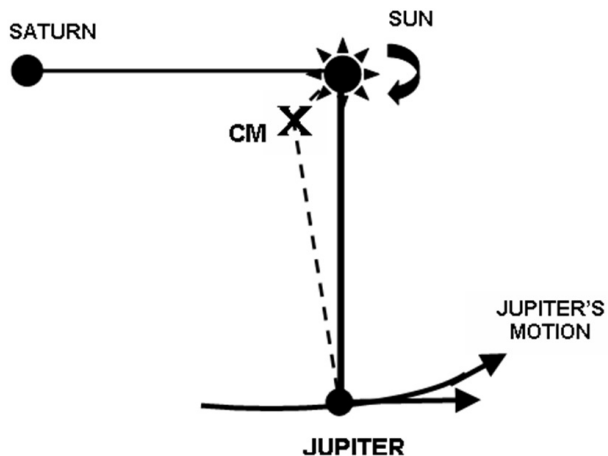
McCracken (Years)	Cycle name	Wilson (2013) (Years)
<b>(i) Category A</b> Periods shorter than the Eddy cycle		
87.3 ± 0.4	Gleissberg	88.15 = 1/2 × 176.3
130 ± 0.9		–
148 ± 1.3		–
350 ± 7		352.6 = 2 × 176.3
510 ± 15		528.9 = 3 × 176.3
708 ± 28		705.2 = 4 × 176.3
<b>(ii) Category B</b> Periods as long or longer than the Eddy cycle		
976 ± 53	Eddy	974.7 = 1151.0 – 176.3?
1126 ± 71		1151.0 = 2 × 575.518
1301 ± 96		1327.3 = 1151.0 + 176.3?
1768 ± 174		1726.5 = 3 × 575.518 (& 1763 = 10 × 176.3)
2310 ± 304	Hallstatt	2302.1 = 4 × 575.518
<b>(iii) Category C</b> Multiples of the de Vries cycle		
104.5 ± 0.6	half de Vries	–
208 ± 2.4	de Vries	208.2

sultant rotation of the face of the club head (red arrow) applies a side-ways force to the golf ball at the point of contact, producing an anti-clockwise rotation (blue arrow) of the ball.

The golf club analogy is good at giving a preliminary introduction to the gear effect. However, there are ambiguities in the analogy that limit its application in the current context. Figure 7b shows a more specific example that removes many of ambiguities of the golf club analogy. In this figure, the head of the golf club is replaced by a structure that consists of three spheres A, B, and C, that are held together by rigid bars (as shown in Fig. 7b). The ABC structure is free to rotate in the plane of the page about a centre-of-mass (CM1). CM1 is located at a fixed distance from the sphere A, as well as a fixed point on the page. Similarly, the golf ball is replaced by a structure that consists of two spheres A and D. These spheres are held together by a rigid bar (as shown in Fig. 7b). The AD structure is free to rotate in the plane of the page about a centre-of-mass (CM2). CM2 is located a fixed distance from the sphere A, however it is able to move freely in the plane of the page.

Now, imagine that a force is applied to sphere A that acts directly along the rigid bar AD towards the sphere D. This could be accomplished by someone pulling on sphere D. Such a force will cause the ABC structure to rotate in a clockwise direction about CM1. One direct consequence of this action is that CM2 will be moved slightly away from CM1 and that both B and D will be forced to rotate around CM2. It is this forced rotation of A and D around CM2, which the present author terms “the gear effect”.

The purpose of this article is to show how the gear effect can be combined with the VEJ tidal-torquing model to



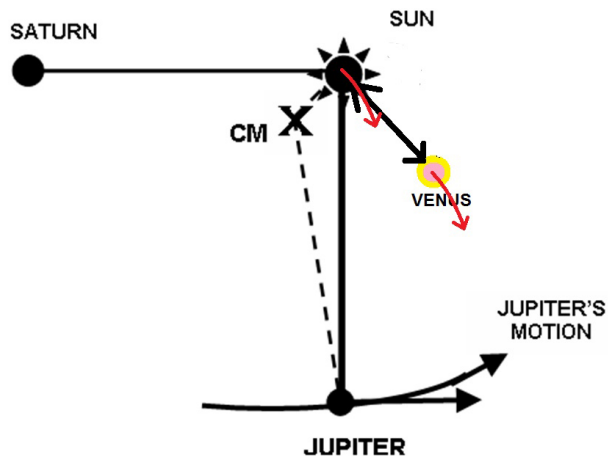
**Figure 8.** The orbital configuration when Jupiter and Saturn are in quadrature with Saturn following Jupiter in its orbit. Saturn drags the centre-of-mass of the Sun, Jupiter, Saturn system (CMSJSa) off the line joining the planet Jupiter to the Sun. As a result, the gravitational force of the Sun acting upon Jupiter speeds up its orbital motion around the CMSJSa. At the same time, the gravitational force of Jupiter acting on the Sun slows down the orbital speed of the Sun around the CMSJSa. The exchange of orbital angular momentum between the Sun and Jupiter is known as the quadrature effect.

produce a spin–orbit coupling model that links the rotation rate of the outer layers of the Sun to the Sun’s motion around the centre-of-mass of the solar system (CMSS). In order to understand how the gear effect can be combined with the VEJ tidal-torquing model, we must, however, also discuss the quadrature effect.

### 3.2 The quadrature effect

Every  $9.9 \pm 1.0$  yr, the planet Saturn is in quadrature with the planet Jupiter (i.e. the subtended angle between Saturn and Jupiter, as seen from the Sun, is 90 degrees). Figure 8 shows the orbital configuration when Jupiter and Saturn are in quadrature with Saturn following Jupiter in its orbit. Referring to this diagram, one can see that Saturn drags the centre-of-mass of the Sun, Jupiter, Saturn system (CMSJSa) off the line joining the planet Jupiter to the Sun. As a result, the gravitational force of the Sun acting upon Jupiter speeds up its orbital motion around the CMSJSa. At the same time, the gravitational force of Jupiter acting on the Sun slows down the orbital speed of the Sun about the CMSJSa. Of course, the reverse is true at the next quadrature, when Saturn precedes Jupiter in its orbit. In this planetary configuration, the mutual force of gravitation between the Sun and Jupiter slows down Jupiter’s orbital motion around the CMSJSa and speeds up the Sun’s orbital motion around the CMSJSa.

Hence, the Sun’s orbital speed around the CMSJSa (as well as the CMSS) should periodically decrease and then increase as we move from one quadrature to the next (Jose,



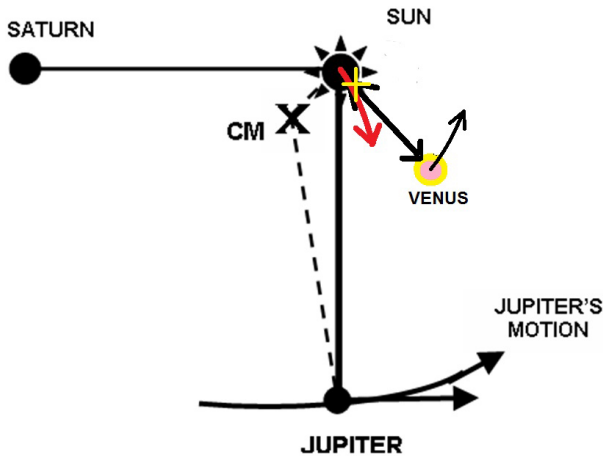
**Figure 9.** A re-plot of Fig. 8 with the terrestrial planet Venus preceding Jupiter in its orbit. This figure shows Saturn and Jupiter in quadrature, with Saturn following Jupiter. Under these circumstances, the quadrature effect ensures that the Sun’s speed around the CMSJSa slows down. If this is the case then the same must be true for the terrestrial planets, since their orbital motions are constrained to move around the centre-of-mass of the Sun rather than the CMSJSa. The red arrows in this figure represent the decrease in speed of the Sun and Venus as they revolve in an anti-clockwise direction around the CMSJSa. This decrease in speed is shared by both the Sun and Venus so that the two bodies effectively move as one, maintaining their orientation and spacing.

1965). This change in speed of the Sun around the CMSJSa once every 19.859 yr is known as the quadrature effect (Wilson et al., 2008).

### 3.3 Differentiating between the quadrature effect and the gear effect

Figure 9 is a re-plot of Fig. 8 with the terrestrial planet Venus preceding Jupiter in its orbit. As with Fig. 8, Fig. 9 shows Saturn and Jupiter in quadrature, with Saturn following Jupiter. Under these circumstances, the quadrature effect ensures that the Sun’s anti-clockwise motion around the CMSJSa will be slowed by the gravitational force of Jupiter. If this is the case, then the same must be true for the terrestrial planets, since their orbital motions are, for all intents and purposes, constrained to move around the centre-of-mass of the Sun rather than the CMSJSa. The red arrows in Fig. 9 represent the decrease in speed of the Sun and Venus as they revolve in an anti-clockwise direction around the CMSJSa. This decrease in speed is shared by both the Sun and Venus so that the two bodies effectively move as one, maintaining their orientation and spacing. Hence, the quadrature effect has little to no effect upon the tangential torques being applied to the outer layer of the Sun by the VEJ tidal-torquing model.

Figure 10 shows the Jupiter–Sun–Saturn system with its CM located at CMSJSa. This is the analogue of the ABC



**Figure 10.** The Jupiter–Sun–Saturn system with its CM located at CMSJSa. This system is the analogue of the ABC structure, described in Sect. 3.1. The figure also shows the Sun–Venus system with its own independent CM. This is the analogue of the AD structure in Sect. 3.1. Now consider the situation where Venus applies a gravitational torque to the Sun that forces the Jupiter–Sun–Saturn system to reduce its orbital velocities around the CMSJSa (red arrow). One direct consequence of this is that the Jupiter–Sun–Saturn system will also apply a gravitational torque to Venus that speeds up the motion of Venus around the CMSJSa (dark curved arrow emanating from Venus). Hence, unlike the quadrature effect, the torques applied in the gear effect try to change the orientation and spacing between the Sun and Venus.

structure, described in Sect. 3.1. Figure 10 also shows the Sun–Venus system with its own independent CM. This is the analogue of the BD structure in Sect. 3.1. Now consider the situation where Venus applies a gravitational torque to the Sun that forces the Jupiter–Sun–Saturn system to reduce its orbital velocities around the CMSJSa (red arrow). One direct consequence of this is that the Jupiter–Sun–Saturn system will also apply a gravitational torque to Venus that speeds up the motion of Venus around the CMSJSa (dark curved arrow emanating from Venus).

Hence, Fig. 10 shows us that there are three critical features that distinguish the gear effect from the quadrature effect:

1. Unlike the quadrature effect, the torques involved in the gear effect try to change the orientation and spacing between the Sun and Venus, for example, in relation to the specific case shown in Fig. 10; even though these gravitational torques are very minute, they produce a net anti-clockwise rotation of the Sun and Venus around their mutual centre-of-mass (yellow cross). (NB: it is the offset between the CMSJSa and the centre-of-mass of the Sun–Venus system that is crucial for producing the net anti-clockwise rotation of the Sun and Venus around their mutual centre-of-mass.)
2. Even though the net gravitational torque tries to produce an anti-clockwise rotation of the Sun and Venus around their mutual centre-of-mass, some of the resulting angular momentum will almost certainly end up changing the rotation rates of both Venus and the outer layers of the Sun.
3. Given the minute nature of the torques applied and velocity changes involved, it is obvious that the effects of the gear effect will be greatest at the times when Venus and the Earth are aligned on the same side of the Sun (i.e. inferior conjunction). At these times, the Jupiter–Sun–Saturn system (which is at quadrature) would experience the combined gravitational force of Venus and the Earth, and the centre-of-mass of the aligned Sun–Venus–Earth system would be furthest from the centre of the Sun.

Hence, the gear effect should have an effect upon the tangential torques applied to the outer layers of the Sun by the VEJ tidal-torquing model and so it will modulate the changes in the rotation rate that are caused by the tidal-torquing mechanism.

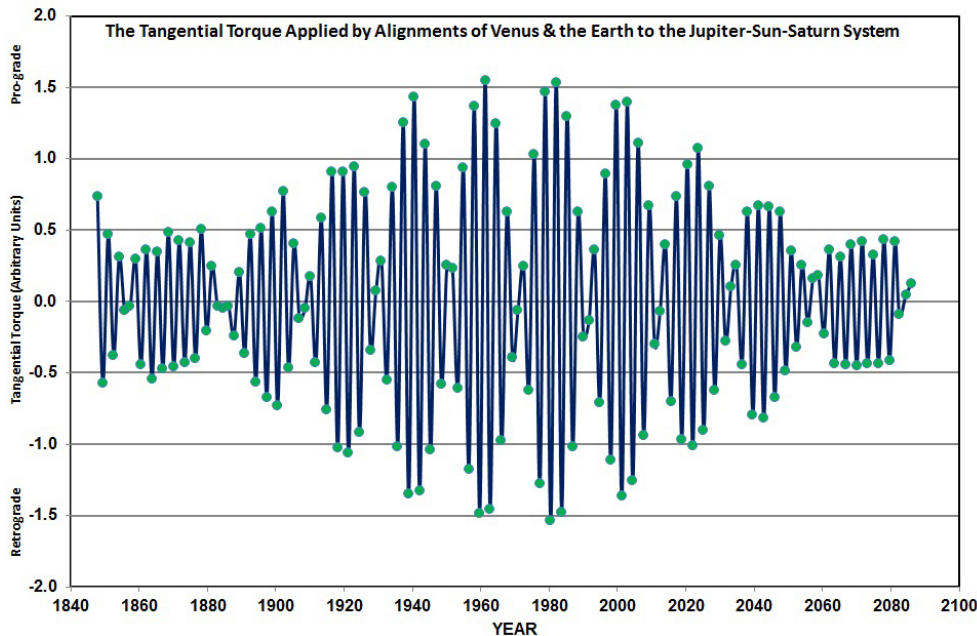
Figure 11 shows the tangential torque applied by the alignments of Venus and Earth to the Jupiter–Sun–Saturn System (via the gear effect acting about the CMSJSa) plotted against time. It is important to note that the quantity plotted is not the actual tangential torque but a variable that is directly proportional to it. This variable is plotted in arbitrary units with positive values indicating that the torque is applied in a prograde direction and negative values indicating that it is applied in a retrograde direction. The data covers the period from October 1847 to December 2085 (Aciqua, 2008).

From Fig. 11 it is evident that both the retrograde and prograde torques varied in a quasi-sinusoidal manner throughout the 20th century and the first half of 21st century. A closer inspection reveals that the torque oscillates between being retrograde and prograde in direction over a period of 3.2 yr. These retrograde/prograde pairs persist over a 20 yr interval, with each bi-decadal period being separated from the next by two (or more) torques that act in the same direction. It is reasonable to presume that the length of the bi-decadal period is set by the 19.859 yr synodic cycle of Jupiter and Saturn.

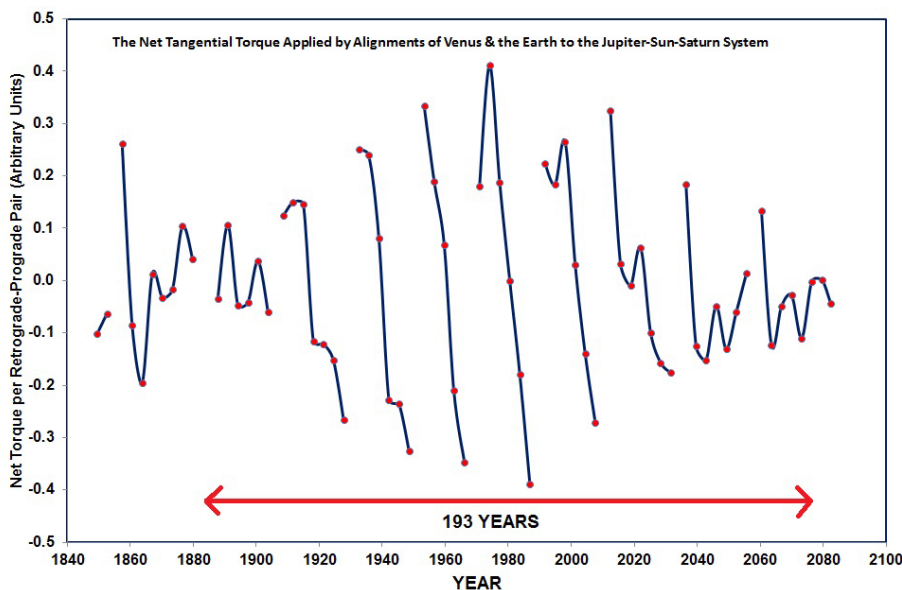
In Fig. 12, the sums of the consecutive retrograde and pro-grade tangential torques shown in Fig. 11 are re-plotted against time. This allows us to see the long-term modulation of the net tangential torque acting upon the convective layers of the Sun between 1847 and 2085. As with Fig. 11, there is a bi-decadal pattern in the net torque produced by the gear effect that is set by the 19.859 yr synodic period of Jupiter and Saturn. However, there is also a longer term modulation of this pattern with a repetition period of approximately 193 yr.

Finally, Fig. 13 shows the angle subtended at the Sun by Venus and Earth (at inferior conjunction) and the centre-of-mass of the Sun–Jupiter–Saturn system, near each quadrature of Jupiter and Saturn, over the period from January 1003 to





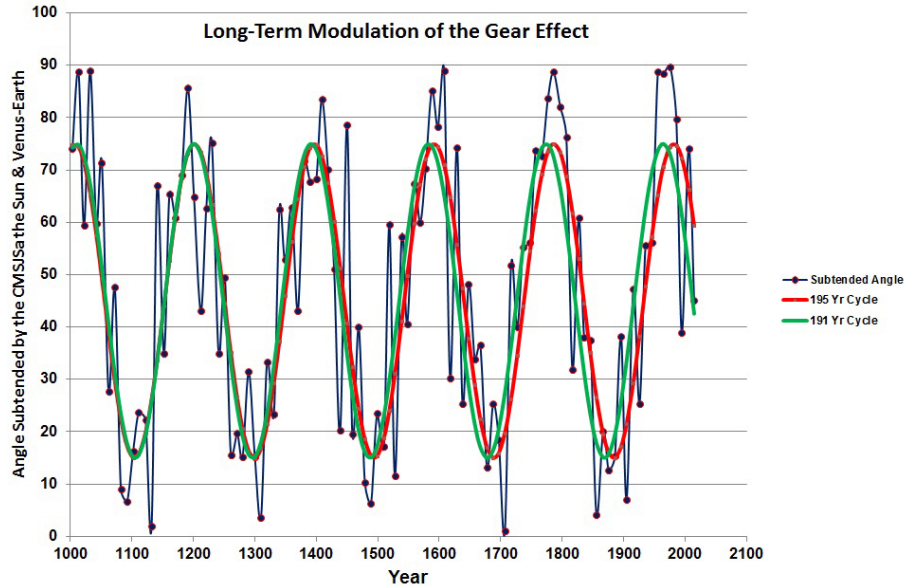
**Figure 11.** The tangential torque applied by the alignments of Venus and Earth to the Jupiter–Sun–Saturn System (via the gear effect acting around the CMSJSa) plotted against time. It is important to note that the quantity plotted is not the actual tangential torque but a variable that is directly proportional to it. This variable is plotted in arbitrary units with positive values indicating that the torque is applied in a pro-grade direction and negative values indicating that it is applied in a retrograde direction. The data covers the period from October 1847 to December 2085.



**Figure 12.** The sum of the consecutive retrograde and pro-grade tangential torques from Fig. 11, replotted against time. As with Fig. 11, there is a bi-decadal pattern in the net torque produced by the gear effect that is set by the 19.859 yr synodic period of Jupiter and Saturn. There is also a longer term modulation of this pattern with a repetition period of approximately 193 yr.

January 2015 (Aciqra, 2008). This plot shows that the tangential torques resulting from the gear effect are greatest when this subtended angle approaches  $90^\circ$  and least when the subtended angle approaches  $0^\circ$ .

Superimposed upon the data plotted in Fig. 13 are two sinusoidal functions with periods of 191.0 and 195.0 yr, synchronized to match in the year 1153. These two sinusoidal curves indicate that the longer term periodicity that



**Figure 13.** The angle subtended by Venus and Earth (at inferior conjunction) and the centre-of-mass of the Sun-Jupiter-Saturn system at the Sun, near each quadrature of Jupiter and Saturn over the period from January 1003 to January 2015. Superimposed upon the data are two sinusoidal functions with periods of 191.0 and 195.0 yr, synchronized to match in the year 1153. These two sinusoidal curves indicate that the longer term periodicity that is modulating the net torque produced by the gear effect has a period  $\approx 193 \pm 2$  yr.

is modulating the net torque produced by the gear effect has a period  $\approx 193 \pm 2$  yr. This long-term modulation cycle is almost certainly set by the time it takes for the 22.137 yr period associated with the VEJ tidal-torquing model to re-align with the 19.859 yr period associated with the gear effect:

$$(22.137 \times 19.859)/(22.137 - 19.859) = 192.98 \text{ yr.} \quad (1)$$

#### 4 Conclusions

There are at least two ways that the Jovian and Terrestrial planets can influence bulk motions in the convective layers of the Sun. The first is via the VEJ tidal-torquing process:

- Tidal bulges are formed at the base of the convective layers of the Sun by the periodical alignments of Venus and the Earth.
- Jupiter applies a tangential gravitational torque to these tidal bulges that either speed-up or slow-down parts of the convective layer of the Sun.
- Jupiter’s net tangential torque increases the rotation rate of the convective layers of the Sun for 11.07 yr ( $\approx 7$  Venus–Earth alignments lasting 11.19 yr) and then decreases the rotation rate over the next 11.07 yr.
- The model produces periodic changes in rotation rate of the convective layers of the Sun that result a 22.14 yr (Hale-like) modulation of the solar activity cycle ( $\approx 14$  Venus–Earth alignments lasting 22.38 yr).

- There is a long-term modulation of the net torque that has a period of  $\approx 166$  yr. This 166 yr modulation period results from the fact that 14 sidereal orbital periods of Jupiter (= 166.07 yr) almost equals 15 times the period required for Jupiter to move  $90^\circ$  in the Venus–Earth alignment reference frame =  $15 \times 11.0683$  yr (= 166.02 yr).

NB: More precisely, it is the mean time required for the 11.8622 yr periodic change in Jupiter’s distance from the Sun to realign with the 11.0683 yr tidal-torquing cycle of the VEJ model.

$$(11.8622 \times 11.0683)/(11.8622 - 11.0683) = 165.38 \text{ yr} \quad (2)$$

The second way is via modulation of the VEJ tidal-torquing process via the gear effect:

- The gear effect modulates the changes in rotation rate of the outer convective layers of the Sun that are being driven by the VEJ tidal-torquing effect.
- This modulation is greatest whenever Saturn is in quadrature with Jupiter. These periodic changes in the modulation of the rotation rate vary over a 19.859 yr period.
- The gear effect is most effective at the times when Venus and the Earth are aligned on the same side of the Sun.
- There is a long-term modulation of the net torque that has a period of 192.98 yr.

While the VEJ tidal-torquing model can produce torques that have periods that closely match the length and phase of the 11.1 Schwabe cycle and the 22.1 yr Hale sunspot cycles, the model cannot easily reproduce the periods that are found by McCracken et al. (2013) for the long-term variations in the level of solar activity. In order to accomplish this, the VEJ tidal-torquing model must be combined with the gear effect to produce a new model called the VEJ spin–orbit coupling model. (NB: this new model is called a spin–orbit coupling model for the simple reason that its net outcome is to produce link between changes in the rotation rate of the convective layers of the Sun (SPIN), primarily near the Sun’s equatorial regions, and changes in the Sun’s motion around the CMSS (ORBIT)).

The new model produces torques with periodicities that fall into three broad categories (Table 1).

#### 4.1 Category A – from the Gleissberg cycle, up to, but not including the Eddy cycle

These periods are produced by the synodic product of short periodicities that are associated with each of the models (i.e. 22.38 yr period for the VEJ tidal-torquing model and 19.859 yr period for the gear effect) such that

$$(22.38 \times 19.859)/(22.38 - 19.859) = 176.30 \text{ yr.} \quad (3)$$

as well as the following multiples of the 176.30 yr period:

$$\begin{aligned} 1/2 \times 176.30 &= 88.15 \text{ yr} - \text{Gleissberg cycle} & 2 \times 176.30 &= 352.6 \text{ yr} \\ 3 \times 176.30 &= 528.9 \text{ yr} & 4 \times 176.30 &= 705.2 \text{ yr} \end{aligned}$$

It is important to note that the 22.38 yr VEJ tidal-torquing cycle is used here in the synodic product rather than the 22.14 yr cycle, since the gear effect interacts with the VEJ tidal-torquing mechanism via the VE alignments. This means that the interaction will take place at the 22.38 yr VE alignment repetition cycle. It also means that the 22.38 yr interaction cycle will slowly drift out of phase with the 22.14 yr torque application cycle, requiring some form of re-synchronization between these two cycles on longer term timescales.

#### 4.2 Category B – the Eddy cycle and periods longer than the Eddy cycle

These periods are produced by a repetition cycle that is close to multiples of the synodic product of the longer modulating periods that are associated with each of the models (i.e. 165.35 yr period for the VEJ tidal-torquing model and 192.98 yr period for the gear effect) such that:

$$(165.38 \times 192.98)/(192.98 - 165.38) = 1156.3 \text{ yr.} \quad (4)$$

It takes Jupiter 575.518 yr to re-synchronize itself with the penta-synodic Venus–Earth alignment cycle. In addition, it takes two 575.518 yr periods (= 1151.0 yr) for Jupiter to re-synchronize itself with the penta-synodic Venus–Earth alignment cycle and also with respect to the stars (Wilson, 2013).

Hence, the 1156.3 yr is most likely just a multiple of the fundamental Jupiter re-synchronization period of 575.518 yr.

These multiples of the 575.518 yr Jupiter re-synchronization cycle include:

$$\begin{aligned} 2 \times 575.518 &= 1151.0 \text{ yr} & 3 \times 575.518 &= 1726.5 \text{ yr} \\ 4 \times 575.518 &= 2302.1 \text{ yr} & &= \text{Hallstatt cycle.} \end{aligned}$$

#### 4.3 Category C – the de Vries cycle and sub-multiples of the de Vries cycle

Finally, the synodic product of the 176.30 yr cycle with the 1151.0 yr cycle is

$$(1151.0 \times 176.30)/(1151.0 - 176.30) = 208.2 \text{ yr.} \quad (5)$$

This is very close to the 208 yr de Vries cycle.

Hence, the new model called the VEJ spin–orbit coupling model, formed by combining the VEJ tidal-torquing model with the gear effect, is able to produce many of the long-term periods in solar activity that are found by McCracken et al. (2013) from proxy  $^{10}\text{Be}$  and  $^{14}\text{C}$  data spanning the last 9400 yr (compare columns 1 and 3 of Table 1).

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