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Proposed Wave Momentum Source for Generating the 22-Year Solar Cycle

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Abstract

For the 22-year solar cycle oscillation there is no external time dependent source. A nonlinear oscillation, the solar cycle must be generated internally, and Babcock-Leighton models apply an artificial nonlinear source term that can simulate the observations—which leaves open the question of the actual source mechanism for the solar cycle. Addressing this question, we propose to take guidance from the wave mechanism that generates the 2-year Quasi-biennial Oscillation (QBO) in the Earth atmosphere. Upward propagating gravity waves, eastward and westward, deposit momentum to generate the observed zonal wind oscillation. On the Sun, helioseismology has provided a thorough understanding of the acoustic p-waves, which propagate down into the convective envelope guided by the increasing temperature and related propagation velocity. Near the tachocline with low turbulent viscosity, the waves propagating eastward and westward can produce an axisymmetric 22-year oscillation of the zonal flow velocities that can generate the magnetic solar dynamo. Following the Earth model, waves in opposite directions can generate in the Sun wind and magnetic field oscillations in opposite directions, the proposition of a potential solar cycle mechanism.

Keywords

Dynamo Models Apply Artificial Nonlinearity, Wave Generated Nonlinear Terrestrial 2-Year Oscillation Model-Analogue Example, Helioseismology Wave Source Proposed for Solar Cycle Mechanism

1. Introduction

Unlike the 12-hour lunar tide that is generated by the gravitational interaction of the Moon around the Earth, a linear oscillation, there is no external time dependent source for the solar cycle. The 22-year variation of the Sun is a nonlinear

*Retired.

oscillation that must be generated internally—and the nonlinear source applied in Babcock-Leighton models can simulate the observed variations of the dipole magnetic field (e.g., Dikpati and Charbonneau [1]).

Discussed in Section 2, the solar oscillation is generated with an artificial nonlinear source term that has been formulated based on the observed evolution and build-up of the toroidal and poloidal magnetic fields during the solar cycle (Babcock [2]; Leighton [3]). This raises the question what the actual mechanism is that generates the solar cycle variation.

Addressing this question, we propose that wave interactions can provide the momentum source for the 22-year oscillation. Waves propagating in opposite directions are a natural source for generating oscillations. And this mechanism has been explored and applied in the Earth atmosphere, where eastward-westward propagating gravity waves generate the observed 2-year Quasi-biennial Oscillation (QBO) of the eastward-westward zonal wind velocities discussed in Section 3. The wave interaction that generates the QBO serves as model-analogue for the solar cycle mechanism.

The proposed wave mechanism can readily be applied in the Sun where helioseismology has provided a thorough understanding of the p-waves that propagate through the convective envelope of the Sun. Over decades, wave observations with Doppler measurements have been applied to explore the convection region with differential rotation, discussed in Section 4.

With advanced understanding of wave dynamics, both on Earth and in the Sun, the proposed wave mechanism is a potent and natural source for the excitation of the 22-year solar cycle oscillation—cross fertilization between terrestrial and solar atmosphere dynamics. Advanced understanding of the p-waves gained from helioseismology can serve to formulate/develop, and apply, the proposed source mechanism for the solar cycle—the motivation and purpose of the present paper discussed in Section 5.

2. Solar Dynamo Models

Charbonneau [4] reviewed the extensive literature on magneto hydrodynamic (MHD) dynamo models of the 22-year solar cycle and related observations. Pars pro toto, we refer to the model of Dikpati and Charbonneau [1], which is built on the early developments of Babcock [2] and Leighton [3]. Dikpati and Charbonneau [1] generate the solar oscillation with a kinematic 2D zonal-mean magnetic field model that simulates the toroidal and radial magnetic fields varying with a period of 20 years.

The dynamo model of Dikpati and Charbonneau [1] is generated with an artificial source term for the poloidal magnetic field

$$S\left(r,\theta;B_\varphi\right) \propto \left[1+\left(\frac{B_\varphi\left(r_c,\theta,t\right)}{B_o}\right)^2\right]^{-1} \times \left[\sin\theta\cos\theta\right] \times B_\varphi\left(r_c,\theta,t\right), \tag{1}$$

which is presented here in a Taylor series expansion

$$\propto [\sin\theta\cos\theta]\times\left[B_\varphi - \frac{B_\varphi^3}{B_o^2} + \frac{B_\varphi^5}{B_o^4} + \cdots\right], \text{ with variable } B_\varphi(r_c, \theta, t). \tag{1a}$$

Here B_φ represents the toroidal magnetic field, (r, θ) are spherical polar coordinates (r_c, for the tachocline region), and the value $B_o = 10^5$ G is chosen.

The nonlinearity of the source term in Equation (1a), the only nonlinear term in the model, has the property that it is of odd (e.g., 3rd) power, and the nonlinearity points into the direction of the oscillating B_φ. With solar cycle frequency, ω, and complex notation, a source in the form $\propto$ $[\mathrm{Exp}(i\omega t)]^{3\#}$ produces the term with $\mathrm{Exp}[i(\omega + \omega + \omega)t]$ for the higher order frequency, 3ω. But the source also generates $\mathrm{Exp}[i(\omega + \omega - \omega)t]$ for the fundamental frequency ω, that maintains the oscillation. (In Babcock-Leighton dynamo models, the nonlinear source term has the character of the momentum source that generates the zonal winds of the quasi-biennial oscillations (QBO) discussed in Section 3).

In the MHD model of Dikpati and Charbonneau [1], the solar differential rotation and meridional flow velocities are applied that are taken from helioseismology (e.g., Scherrer *et al.* [5]). And a height dependent magnetic diffusivity is applied to control the buoyancy and oscillation period of the magnetic field.

The nonlinear Babcock-Leighton source mechanism (Equation (1)) has also been applied in a full MHD model that generates the zonal and meridional flow velocities (Rempel [6]). The resulting magnetic field variations reproduce the observed patterns of the 22-year solar cycle.

Magnetic field variations in the Sun can be generated without the artificial Babcock-Leighton source (e.g., Brun *et al.*, [7]). In this 3D model, vector spherical harmonics are employed to provide solutions of the nonlinear MHD equations with turbulence, covering the convective envelop of the Sun above the tachocline. For the sub-grid flow velocities and magnetic fields, the eddy diffusivity is parameterized to produce globally uniform variations, increasing with altitude inversely proportional to the square-root of the background density. The model explores the dynamical properties of the solar dynamo, which shows that the amplitude and period of the oscillation increase with decreasing diffusivity. The dynamo results for the lowest diffusivity have periods around 3 years (Figure 11 of Brun *et al.* [7]).

3. Wave Generated Oscillations in the Terrestrial Atmosphere

In the zonal circulation of the Earth lower atmosphere at equatorial latitudes, the Quasi-biennial Oscillation (QBO) dominates with periods between 20 and 32 months. Lindzen and Holton [8], and Holton and Lindzen [9] demonstrated that the QBO can be generated with global-scale long-period planetary waves (PW), eastward propagating Kelvin waves and westward propagating Rossby Gravity waves. Modeling studies with realistic PW have shown that small-scale short-period gravity waves (GW), with isotropic propagation, are more effective in generating the QBO (e.g., Hitchman and Leovy [10]). Dealing with the observed

$\mathrm{Cos}(\omega t)^3 = \mathrm{Cos}(3\omega t)/4 + 3\mathrm{Cos}(\omega t)/4$.

broad frequency spectrum and short horizontal wave lengths, the GW interaction with the atmosphere was parameterized, and several models have shown that the wave source can generate the QBO (e.g., Mengel *et al.* [11]; Dunkerton [12]; Akmaev [13]).

We present here the computed zonal winds generated with the 3D Numerical Spectral Model (NSM), fully nonlinear, which was developed by Chan *et al.* [14]. Starting with Mengel *et al.* [11] and Mayr *et al.* [15], the NSM has been run with the Doppler Spread Parameterization (DSP) for GW momentum deposition (Hines [16] [17]). The DSP deals with a spectrum of waves and accounts for nonlinear interactions that produce Doppler spreading, which is important for the wave interaction that generates the GW momentum source and eddy viscosity. In **Figure 1** are shown the results for the zonal winds with QBO period of 30 months, which was generated with the 2D version of the NSM and with latitude independent GW source (Mayr *et al.* [18]). In **Figure 1(a)**, the altitude variations are presented at 4˚ latitude, and in **Figure 1(b)** the variations with latitude at about 20 km.

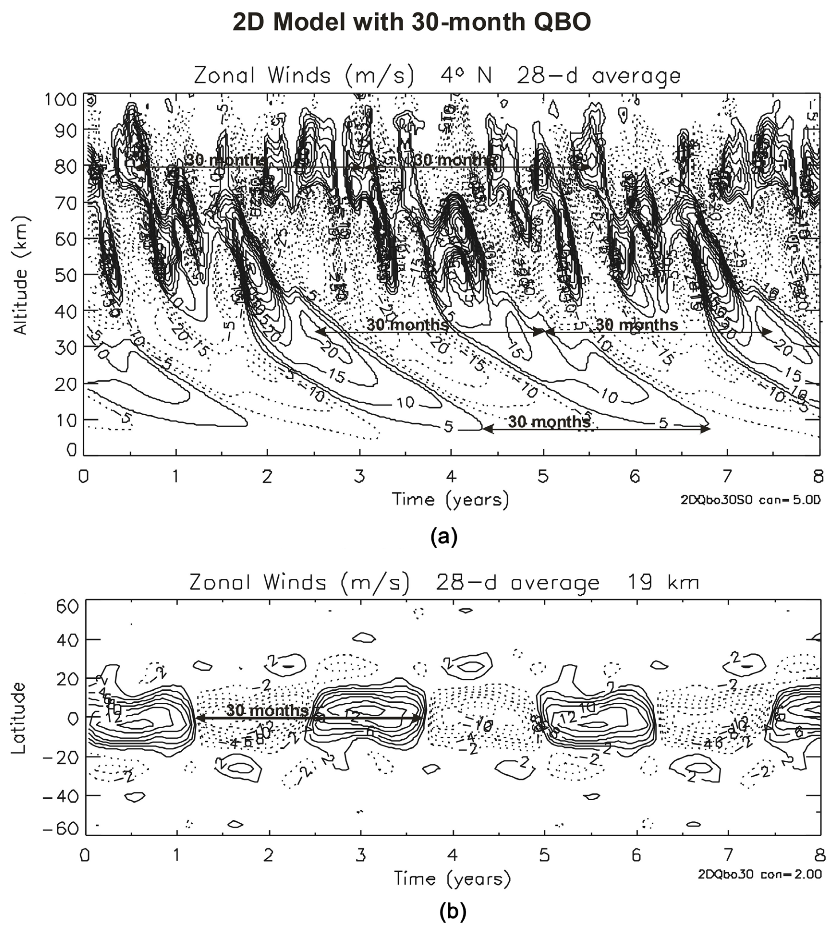

Figure 1. (a) Zonal winds near the equator with QBO oscillation period of 30 months plotted versus altitudes. (b) Latitudinal variations at about 20 km show that the oscillation is confined to low latitudes as observed; it is generated with a globally uniform gravity wave (GW) momentum source (Figure taken from Mayr *et al.* [18]).

Lindzen and Holton [8] discussed and emphasized the unique dynamical conditions for generating the QBO at equatorial latitudes, illuminated by the zonal momentum balance,

$$i\rho\omega U + 2\Omega\sin\theta\rho V - K\rho\frac{\partial^2 U}{\partial r^2} = MS, \qquad (2)$$

with standard notations, U, V zonal and meridional winds, K eddy viscosity, and MS wave momentum source. At the equator, $\theta = 0$, where the Coriolis force vanishes, the wave forcing is very effective because it is dissipated only by viscosity. Away from the equator, the meridional circulation increasingly comes into play to redistribute and dissipate the flow oscillation. The zonal winds thus peak at the equator, as shown in **Figure 1(b)**, and in agreement with observations.

The QBO at the equator is solely dissipated by the eddy viscosity/diffusivity, K, and **Figure 2(a)** shows that K increases exponentially as the GW amplitude grows with altitude. The corresponding time constant in **Figure 2(b)** produces periods that decrease with altitude, varying from about 2 years at 35 km to values close to 6 months near 50 km, in qualitative agreement with the oscillation pattern in **Figure 1(a)**.

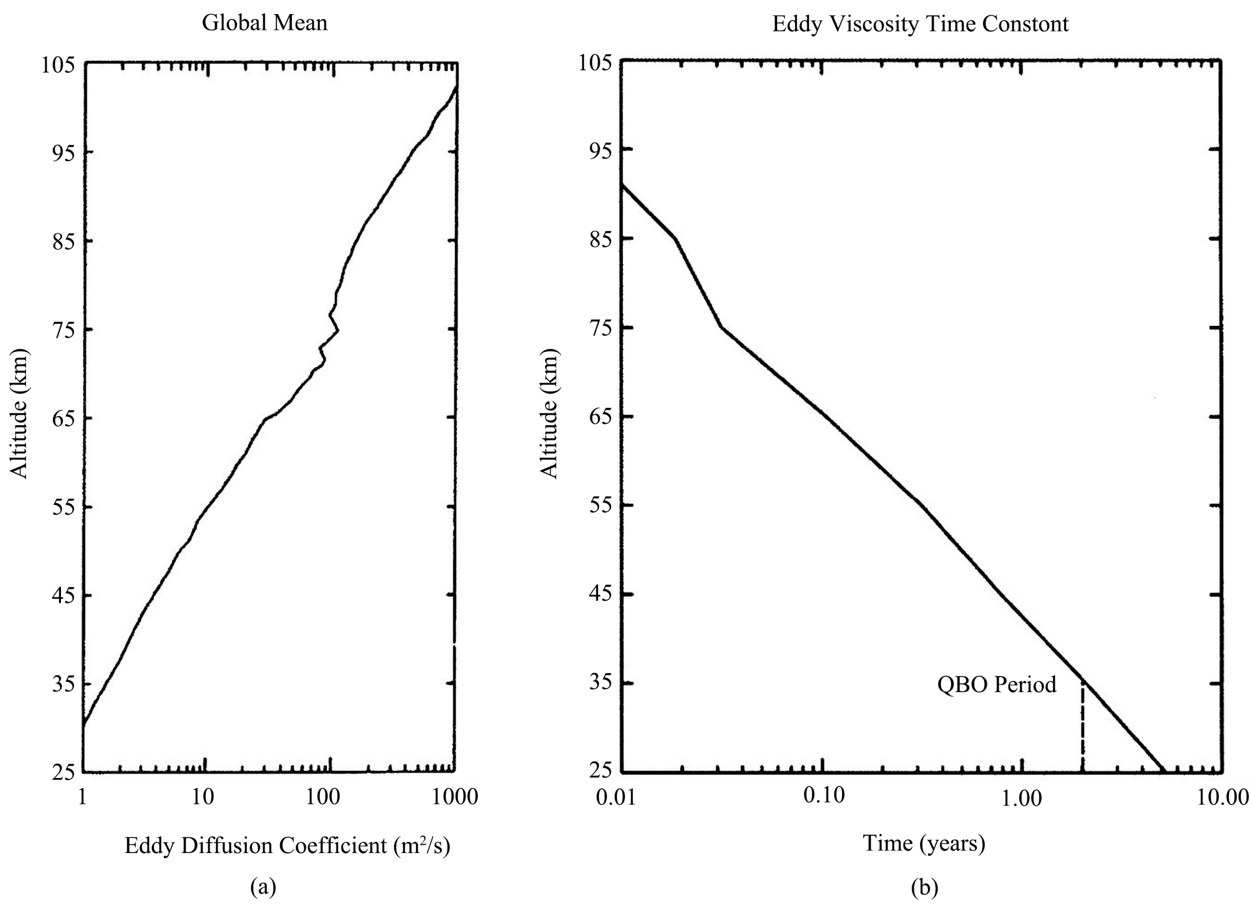

Figure 2. (a) Altitude variation of eddy diffusivity/viscosity that dissipates the zonal winds generated with the numerical model (Figure taken from Mayr *et al.* [15]). (b) Eddy viscosity time constant versus altitude with periods around 2 years for the QBO at around 35 km (Figure taken from Mayr and Schatten [19]).

The connection between dissipation and oscillation period is shown in a computer experiment (Mayr *et al.* [20]) that produces the numerical results presented in **Figure 3**. With identical wave source, the zonal winds were generated with different eddy viscosities. Compared with the zonal winds for Ks, the oscillations with lower viscosity, Ks/2, have periods about a factor of two longer, and the amplitudes are larger by about the same factor.

A numerical experiment, the solutions in **Figure 3** were generated with the Sun fixed at the equator. Without external time dependent solar heating and with constant GW momentum source, QBO-like oscillations are generated in the lower atmosphere. A nonlinear oscillation is generated internally—and the nature/property of the nonlinear momentum source is the question.

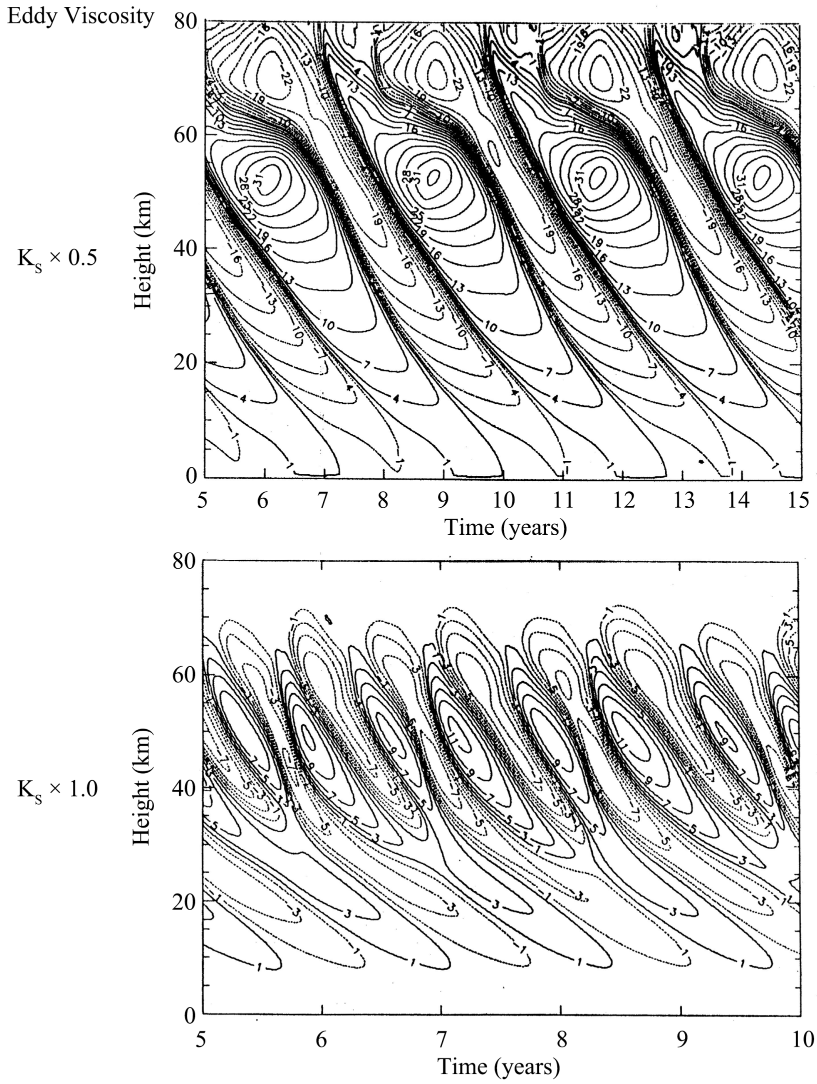

Figure 3. Computed equatorial QBO like oscillations for perpetual equinox without external time dependent source, purely generated by the GW momentum source. Results are presented for the standard eddy diffusivity, Ks, and reduced by a factor of 2. The period and amplitude of the oscillation increase with decreasing K (Figure taken from Mayr *et al.* [20]).

The nonlinearity is displayed in **Figure 4**, which shows snapshots of the zonal winds and accompanying GW momentum source, *MS*, that is sharply peaked near zonal wind shears, dU/dr. This impulsive momentum source can be represented in a form that is, to first order, proportional to the 3rd (or odd) power of the velocity gradient, $\propto [dU/dr]^3$—which has the character of the artificial source term (Equation (1a)) that generates the nonlinear solar cycle oscillation in Babcock-Leighton models (Section 2).

Without external time dependent solar forcing, and applying a constant GW source, waves propagating in the eastward-westward directions can generate QBO-like zonal wind oscillations in opposite directions. And the zonal wind variations are dissipated by the eddy viscosity, which controls the amplitude and period of the oscillation.

4. Helioseismology and Solar Differential Rotation

The energy the Sun emits is carried up from the interior by convection. In the convective solar envelope, the negative vertical temperature gradient is relatively large, larger than the adiabatic lapse rate that is proportional to the gravitational acceleration.

With helioseismology (e.g., Howe [21]; Basu [22]) the variable and radiating density variations at the surface are observed to explore the interior structure of the Sun. The observed wave oscillations, referred to as pressure waves or p-waves, have periods around 5 minutes. The short period high frequency oscillations represent acoustic waves that can propagate through the convective solar envelope. (In the stable terrestrial atmosphere, energized by absorbed solar radiation, the propagating oscillations are gravity waves with periods of order hours.)

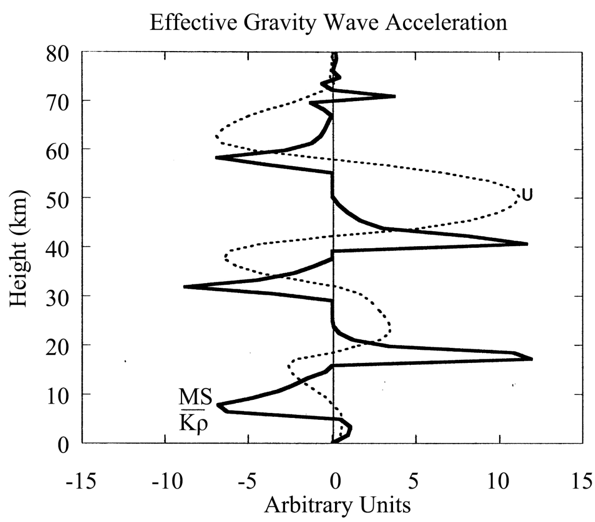

Figure 4. Snapshot of effective gravity wave (GW) momentum source (MS) divided by mass density and eddy viscosity, shown with solid line for comparison with zonal winds, U. The sharp peaks of MS in the direction of the velocity gradients (positive and negative) represent a non-linearity of 3rd (odd) power (Figure taken from Mayr *et al.* [20]).

The acoustic p-waves propagate down into the convection region with the full range of directions like a downward fountain. With increasing temperatures at lower altitudes, the horizontal propagation velocity increases proportional to $T^{1/2}$. The waves thus propagate more and more in the horizontal direction at lower altitudes—until they eventually turn around at the bottom and propagate back to the solar surface. Depending on the direction propagating down, the waves experience the increasing propagation velocities associated with the increasing temperatures at lower altitudes. Waves closer to the radial direction sense the higher propagation velocities deeper in the solar convection region—and waves closer to the horizontal direction are modified by the velocities closer to the surface.

Depending on the temperature and turn-around depth, the waves going down propagate with velocities that are different from the waves that are returning/ refracted to the surface of the Sun. And in the rotating Sun with differential rotation, the resulting Doppler effects determine the propagation velocities observed with helioseismology.

Given the frequencies and Doppler shifted propagation velocities of the acoustic p-waves observed at the solar surface, inversion procedures have been developed with helioseismology to explore the global variations of solar differential rotation inside the convection region (e.g., Paterno [23]). To that end, physical models have been developed and employed to describe the global-scale patterns of the propagating waves, which are delineated in terms of spherical harmonics.

Going back to the 70's, the frequencies and Doppler velocities have been observed over the years with ground based measurements from stations located all over the globe, like the Global Oscillations Network Group (GONG) (e.g. Harvey *et al.* [24]) that covers the entire convection region. And from 1995 to 2010, the Michelson Doppler Imager (MDI) (e.g. Gabriel *et al.* [25]) provided high resolution measurements on the Solar and Heliospheric Observatory (SOHO).

In **Figure 5** are presented the variations of solar differential rotation in the radial direction, taken from Wikipedia. The flow velocities show relatively small variations with altitude. Below the tachocline at 0.7r, the velocities converge to the solar rotation frequency of 430 nHz (27 day period rotation). Larger rotation rates are observed around the equator and lower ones at high latitudes, confined to the convection region above the tachocline.

5. Proposed Wave Momentum Source for 22-Year Solar Cycle

The question is what kind of mechanism, dynamic in nature, could actually generate the solar cycle—and we propose that wave interactions in the solar convection region may provide the momentum source for the 22-year oscillation. This notion is advanced by the gravity wave momentum source that generates the 2-year Quasi-biennial Oscillation (QBO) in the Earth atmosphere. The wave mechanism is potent, because waves propagating in opposite directions are a

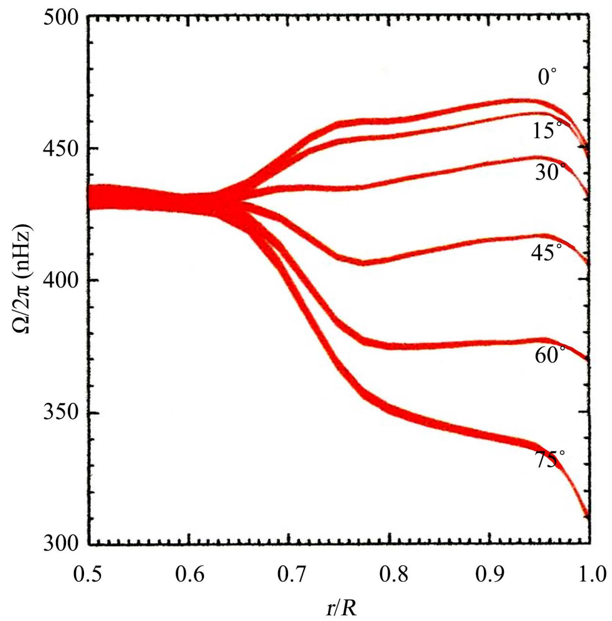

Figure 5. Radial variations of solar differential rotation (Figure taken from Wikipedia).

natural source for reversing oscillations, the eastward-westward vector wind velocities on Earth, and the alternating vector magnetic fields of the solar cycle. The wave mechanism is also appealing for the solar convective envelope, where the acoustic p-waves have been observed and extensively analyzed with helioseismology (e.g., Howe [21]; Basu [22]). With helioseismology a thorough understanding of the propagating p-waves was acquired, which can serve to develop and exploit the wave momentum source for the solar oscillation.

With periods around 5 minutes and relatively large vertical wind velocities, the observed surface oscillations on the Sun represent acoustic p-waves. The waves propagate down into the convection region with increasing temperature and horizontal propagation velocity proportional to $T^{1/2}$. At lower altitudes, the waves propagate increasingly into the horizontal direction, eastward or westward (prograde or retrograde), and finally turn around and propagate back to the surface of the Sun as illustrated in **Figure 6**. Propagating horizontally in opposite directions through the turn-around region at the bottom of their trajectories, the waves can produce a momentum source that generates eastward-westward zonal flow oscillations in the Sun. In the terrestrial atmosphere, the 2-year oscillation is controlled by the time constant for the eddy diffusivity at lower altitudes (**Figure 2(b)**). And in the Sun, the low turbulent diffusivity at the bottom of the convection region (e.g., Brun *et al.* [7]) would favor the 22-year periodicity of the SC oscillation. The tachocline is generally considered to be the source region for the SC dynamo (Chardonneau [4]).

At the base of the convection region, at lower altitudes, the proposed p-wave mechanism is more potent, because the wave trajectories cover more of the horizontal direction. With isotropic uniform downward propagation of the p-waves, the depths of the turn-around trajectory varies with the cos of the radial

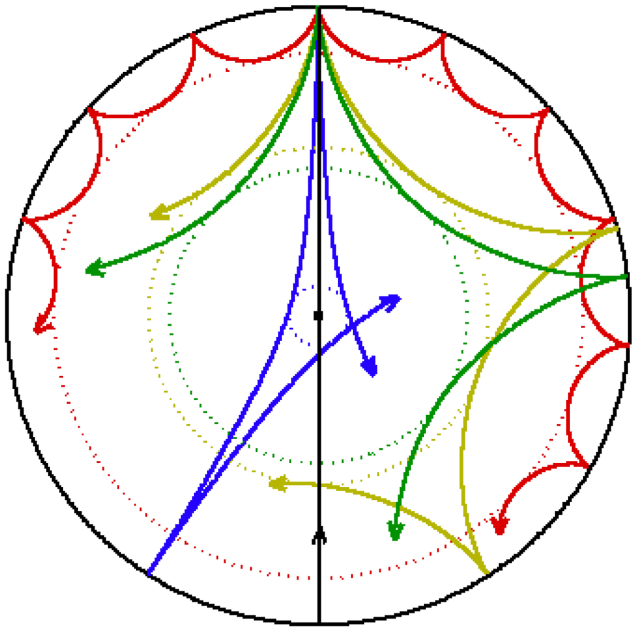

Figure 6. Ray path patterns of p-waves propagating into the Sun (Figure taken from Max Planck Institute for Solar System Research).
http://www2.mps.mpg.de/projects/seismo/SpaceInn/MODEL/travel_time.html

direction. At greater depths near the tachocline, a larger portion of the wave directions/trajectories is involved propagating horizontally with energy dissipation and momentum deposition. And with lower viscosity at the base of the convection region, the wave momentum source is more effective in generating larger eastward-westward flow velocities, as illustrated in **Figure 3** for the terrestrial atmosphere.

The proposed mechanism for the 22-year oscillation in the Sun is taken from the model/analog of the wave mechanism that generates the 2-year Quasi-biennial Oscillation (QBO) in the Earth atmosphere—and here is a juxtaposition of the differences and similarities.

In the stable Earth atmosphere, gravity waves provide the momentum source for the QBO. The waves are generated by turbulence near the ground, covering a wide range of frequencies and vertical wavelengths, and they propagate up to interact with the background atmosphere. Energized by the absorption of solar radiation, the zonal winds in the Earth atmosphere tend to increase with altitude, which affects the propagation and momentum deposition of gravity waves through critical level absorption (Hines and Reddy [26]; Brooks and Bretherton [27]). As the horizontal velocity of the upward propagating waves approaches the background wind velocity at a particular altitude, the critical level, the waves continue propagating at this level and deposit momentum to accelerate the atmosphere in the eastward and westward directions. Absorption of the energy/momentum carried by the upward propagating gravity waves is generating the zonal wind oscillation of the QBO. And wave interactions with the QBO zonal winds amplify the oscillation through the positive nonlinear feedback of critical level absorption. Internally generated by wave interactions, the period of the QBO oscillation is determined by the time constant for the low eddy diffusion rate in the lower atmosphere (**Figure 2(b)**).

The setting for the proposed wave mechanism in the Sun is different. In the convective solar envelope, acoustic p-waves are involved that are observed at the boiling solar surface. The p-waves propagate down towards the base of the convection region where they interact with the background atmosphere. On the Sun, the observed zonal winds of differential rotation are aligned radially (**Figure 5**)—unlike the height variation of the background zonal winds in the terrestrial atmosphere that produces critical level absorption of the propagating gravity waves. The altitude invariant zonal winds are not attracting critical level absorption of p-waves in the Sun. But the p-waves are guided/attracted by the increasing temperature and propagation velocity at lower altitudes in the convection region. Like critical level absorption in the Earth atmosphere, the p-waves are forced by the increasing internal propagation velocity to propagate horizontally eastward and westward (**Figure 6**), which must be accompanied by dissipation and momentum deposition. At lower altitudes near the base of the convection region, the horizontal pathway of the waves is getting longer thus increasing the momentum transferred to the atmosphere. With isotropic propagation, more of the wave energy is also bundled/concentrated at lower altitudes to increase the momentum source, and the resulting zonal flow oscillation can be amplified by nonlinear wave interactions related to critical level absorption. Near the tachocline at lower altitudes in the convection region, the low turbulent viscosity can produce the long time constant that generates the 22-year periodicity of the solar cycle. The overall settings for the Earth and Sun are different—but the dynamical properties for the terrestrial and solar wave mechanisms have much in common—in addition to the fundamental property that propagating waves in opposite directions can readily generate oscillations in opposite directions.

Guided by the seminal theory for the Quasi-biennial Oscillation (QBO) in the Earth atmosphere (Lindzen and Holton [8]), a wave generated flow oscillation has been discussed in a modeling study applied to the stable region of the solar atmosphere below the tachocline (Rogers *et al.* [28]). The oscillation is generated with individual eastward (prograde) and westward (retrograde) propagating waves. Unlike the global scale planetary waves in the terrestrial QBO model with periods of order days, in this model for the Sun small-scale gravity waves (GW) are applied, which have a period close to 6 hours. Run with eddy viscosity 10^{11} cm^2/s, the generated flow oscillation shown in the paper has a period of about 3 months (Figure 1 of Rogers *et al.* [28]). And with viscosity 2×10^{10} cm^2/s, the oscillation period is close to 5 months.

Guided by GW simulations of the terrestrial QBO (Mengel *et al.*, [11]), a 22-year zonal flow oscillation has been generated in a modeling study for the stable solar region below the tachocline (Mayr *et al.* [29]). With a spectrum of waves applied in the Doppler Spread Parameterization (DSP) for GW momentum deposition (Hines [16] [17]), a simplified analytical model (Mayr *et al.* [30]) was employed to explore the zonal flow oscillations in the Sun over a range of values for the eddy diffusion rates and convective stability. With eddy diffusivity/viscosity of about 10^7 cm^2/s, and with wave amplitudes < 10 m/s, the model generates a 22-year oscillation with 20 m/s flow velocities, proposed as excitation source for the observed solar cycle variation of the magnetic field.

The above-discussed scenarios of gravity wave generated flow oscillations in the stable region of the Sun can serve as model guides for the proposed solar cycle mechanism in the convection region with propagating p-waves. Dealing with the observed p-wave spectrum, the SC flow oscillation can be generated with a parameterization of the momentum source akin to the terrestrial model applied in Mayr *et al.* [29].

For the 22-year zonal flow oscillation generated with the proposed wave momentum source, the model scenario of the SC magnetic dynamo is illustrated in **Figure 7** (Mayr *et al.* [29]). With the zonal flow velocities, and Coriolis force, a corresponding oscillation is generated in the meridional circulation. In the ionized plasma of the Sun with background magnetic fields, and Lorentz force, the flow oscillation increases the conductivity. And with enhanced conductivity, the eastward-westward electric current oscillation, driven by the zonal velocities, can in turn generate the reversing northward-southward magnetic field variation of the solar dynamo. Wave generated MHD solar cycle dynamo.

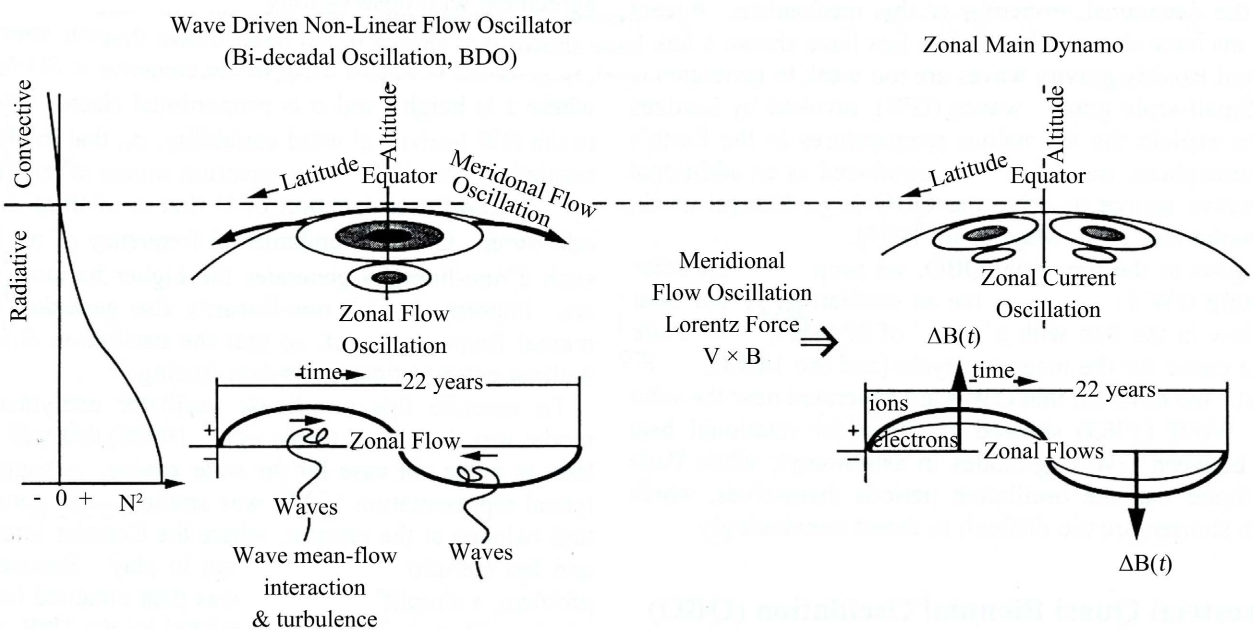

Figure 7. Illustration of the scenario for the solar cycle (SC) dynamo generated with the proposed wave momentum source. (a) In the convective solar atmosphere, the acoustic p-waves generate the eastward-westward zonal flow oscillation, with the 22-year periodicity determined by the turbulent viscosity near the tachocline. With the zonal winds and Coriolis force a corresponding oscillation is generated in the meridional circulation. (b) In the solar plasma with Lorentz force, the circulation increases the conductivity. And the electric currents driven by the eastward-westward flow oscillation can produce the northward-southward oscillating dynamo magnetic field (Figure taken from Mayr *et al.* [29], but applied to the solar convection region).

6. Summary

Without external time dependent source, the 22-year oscillation in the Sun must be generated internally, and the nonlinear artificial source term in Babcock-Leighton models can produce the observed variations of the magnetic field (Section 2). The actual source mechanism of the solar cycle remains an open question—and we propose in this review paper that the wave momentum source for the Quasi-biennial Oscillation (QBO) in the Earth atmosphere can serve as a model-analogue. Discussed in Section 3, gravity waves propagating eastward-westward provide the momentum source for zonal wind oscillations with periods around 2 years controlled by the time constant for eddy diffusion. Generated internally, the nonlinearity of the wave momentum source is of 3rd (odd) order, like the source terms in Babcock-Leighton dynamo models. (A nonlinearity of odd power generates the fundamental frequency in addition to the higher order frequencies, which maintains the oscillation.) The proposed wave mechanism is a natural and potent source for application in the Sun with helioseismology (Section 4), where acoustic p-waves are observed and analyzed to explore the interior of the convective solar envelope. With helioseismology a thorough understanding of the propagating p-waves was acquired, which can serve to formulate the proposed wave momentum source for the zonal circulation that can generate the solar oscillation (Section 5). The atmospheric settings/environments for the propagating waves on Earth and in the Sun are different. Propagating up from the turbulent storm environment near the Earth surface, the gravity waves are channeled by background zonal winds to produce critical level absorption with momentum transfer accelerating the flow. On the Sun, the p-waves propagate down from the boiling surface, and the waves are guided/channeled by the increasing temperature and propagation velocity to propagate horizontally (**Figure 6**). P-waves propagating eastward-westward must produce a momentum source for horizontal flow oscillations in opposite directions. Near the base of the tachocline where the turbulent viscosity is low, the related time constant can facilitate the 22-year oscillation. Solar cycle signatures are observed in the zonal and meridional flow velocities of the Sun (Imada *et al.* [31]) in support of the wave momentum source that is proposed to generate the atmospheric oscillation. A zonal flow oscillation can generate the eastward-westward electric current oscillation to produce the northward-southward solar cycle variation of the dynamo magnetic field illustrated in **Figure 7**.

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Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

References

[1] Dikpati, M. and Charbonneau, P. (1999) A Babcock-Leighton Flux Transport Dynamo with Solar-Like Differential Rotation. *The Astrophysical Journal*, **518**, 508-520. https://doi.org/10.1086/307269

[2] Babcock, H.W. (1961) The Topology of the Sun's Magnetic Field and the 22-Year Cycle. *The Astrophysical Journal*, **133**, 572-589. https://doi.org/10.1086/147060

[3] Leighton, R.B. (1969) A Magneto-Kinematic Model of the Solar Cycle. *The Astrophysical Journal*, **156**, 1-26. https://doi.org/10.1086/149943

[4] Charbonneau, P. (2010) Dynamo Models of the Solar Cycle. *Living Reviews in Solar Physics*, **7**, Article No. 3. https://doi.org/10.12942/lrsp-2010-3

[5] Scherrer, P.H., Bogard, R.S., Bush, R.I., *et al.* (1995) The Solar Oscillations Investigation—Michelson Doppler Imager. *Solar Physics*, **162**, 129-188. https://doi.org/10.1007/978-94-009-0191-9_5

[6] Rempel, M. (2006) Flux-Transport Dynamos with Lorentz Force Feedback on Differential Rotation and Meridional Flow: Saturation Mechanism and Torsional Oscillations. *The Astrophysical Journal*, **647**, 662-675. https://doi.org/10.1086/505170

[7] Brun, A.S., Miesch, M.S. and Toomre, J. (2004) Global-Scale Turbulent Convection and Magnetic Dynamo Action in the Solar Envelope. *The Astrophysical Journal*, **614**, 1073-1098. https://doi.org/10.1086/423835

[8] Lindzen, R.S. and Holton, J.R. (1968) A Theory of the Quasi-Biennial Oscillation. *Journal of the Atmospheric Sciences*, **25**, 1095-1968. https://doi.org/10.1175/1520-0469(1968)025<1095:ATOTQB>2.0.CO;2

[9] Holton, J.R. and Lindzen, R.S. (1972) An Updated Theory for the Quasi-Biennial Cycle of the Tropical Stratosphere. *Journal of the Atmospheric Sciences*, **29**, 1076-1080. https://doi.org/10.1175/1520-0469(1972)029<1076:AUTFTQ>2.0.CO;2

[10] Hitchman, M.H. and Leovy, C.B. (1988) Estimation of the Kelvin Wave Contribution to the Semiannual Oscillation. *Journal of the Atmospheric Sciences*, **45**, 1462-1475. https://doi.org/10.1175/1520-0469(1988)045<1462:EOTKWC>2.0.CO;2

[11] Mengel, J.G., Mayr, H.G., Chan, K.L., Hines, C.O., Reddy, C.A., Arnold, N.F. and Porter, H.S. (1995) Equatorial Oscillations in the Middle Atmosphere Generated by Small Scale Gravity Waves. *Geophysical Research Letters*, **22**, 3027-3030. https://doi.org/10.1029/95GL03059

[12] Dunkerton, T.J. (1997) The Role of the Gravity Waves in the Quasi-Biennial Oscillation. *Journal of Geophysical Research*, **102**, 26053-26076. https://doi.org/10.1029/96JD02999

[13] Akmaev, R.A. (2001) Simulation of Large-Scale Dynamics in the Mesosphere and Lower Thermosphere with the Doppler-Spread Parameterization of Gravity Waves: 1. Implementation and Zonal Mean Climatologies. *Journal of Geophysical Research*, **106**, 1193-1204. https://doi.org/10.1029/2000JD900520

[14] Chan, K.L., Mayr, H.G., Mengel, J.G. and Harris, I. (1994) A "Stratified" Spectral Model for Stable and Convective Atmospheres. *Journal of Computational Physics*, **113**, 165-176. https://doi.org/10.1006/jcph.1994.1128

[15] Mayr, H.G, Mengel, J.G., Hines, C.O., Chan, K.L., Arnold, N.F., Reddy, C.A. and Porter, H.S. (1997) The Gravity Wave Doppler Spread Theory Applied in a Numerical Spectral Model of the Middle Atmosphere, 1, Model and Global-Scale Seasonal Variations. *Journal of Geophysical Research*, **102**, 26077-26091. https://doi.org/10.1029/96JD03213

[16] Hines, C.O. (1997) Doppler-Spread Parameterization of Gravity-Wave Momentum Deposition in the Middle Atmosphere, 1, Basic Formulation. *Journal of Atmos-*

pheric and Solar-Terrestrial Physics, **59**, 371-386.
https://doi.org/10.1016/S1364-6826(96)00079-X

[17] Hines, C.O. (1997) Doppler-Spread Parameterization of Gravity-Wave Momentum Deposition in the Middle Atmosphere, 2, Broad and Quasi Monochromatic Spectra, and Implementation. *Journal of Atmospheric and Solar-Terrestrial Physics*, **59**, 387-400. https://doi.org/10.1016/S1364-6826(96)00080-6

[18] Mayr, H.G, Mengel, J.G., Reddy, C.A., Chan, K.L. and Porter, H.S. (2000) Properties of QBO and SAO Generated by Gravity Waves. *Journal of Atmospheric and Solar-Terrestrial Physics*, **62**, 1135-1154.
https://doi.org/10.1016/S1364-6826(00)00103-6

[19] Mayr, H.G. and Schatten, K.H. (2011) Nonlinear Oscillators in Space Physics. *Journal of Atmospheric and Solar-Terrestrial Physics*, **74**, 44-50.
https://doi.org/10.1016/j.jastp.2011.09.008

[20] Mayr, H.G., Mengel, J.G., Reddy, C.A., Chan, K.L. and Porter, H.S. (1999) The Role of Gravity Waves in Maintaining the QBO and SAO at Equatorial Latitudes. *Advances in Space Research*, **24**, 1531-1541.
https://doi.org/10.1016/S0273-1177(99)00876-5

[21] Howe, R. (2009) Solar Interior Rotation and Its Variation. *Living Reviews in Solar Physics*, **6**, Article No. 1. https://doi.org/10.12942/lrsp-2009-1

[22] Basu, S. (2016) Global Seismology of the Sun. *Living Reviews in Solar Physics*, **13**, Article No. 2. https://doi.org/10.1007/s41116-016-0003-4

[23] Paterno, L. (2010) The Solar Differential Rotation: A Historical Review. *Astrophysics and Space Science*, **328**, 269-277. https://doi.org/10.1007/s10509-009-0218-0

[24] Harvey, J.W., Hill, F., Hubbard, R.P., *et al.* (1996) The Global Observations Network Group (GONG) Project. *Science*, **272**, 1284-1286.
https://doi.org/10.1126/science.272.5266.1284

[25] Gabriel, A.H., Grec, G., Charra, J., *et al.* (1995) Global Oscillations at Low Frequency from the SOHO Mission (GOLF). *Solar Physics*, **162**, 61-99.
https://doi.org/10.1007/978-94-009-0191-9_3

[26] Hines, C.O. and Reddy C.O. (1967) On the Propagation of Atmospheric Gravity Waves through Regions of Wind Shear. *Journal of Geophysical Research*, **72**, 1015-1034. https://doi.org/10.1029/JZ072i003p01015

[27] Booker, J.R. and Breton, F.T. (1967) The Critical Layer for Internal Gravity Waves in a Shear Flow. *Journal of Fluid Mechanics*, **27**, 513-519.
https://doi.org/10.1017/S0022112067000515

[28] Rogers, T.M., MacGregor, K.B. and Glatzmaier, G.A. (2008) Non-Linear Dynamics of Gravity Wave Driven Flows in the Solar Radiative Interior. *Monthly Notices of the Royal Astronomical Society*, **387**, 616-630.
https://doi.org/10.1111/j.1365-2966.2008.13289.x

[29] Mayr, H.G., Wolff, C.L. and Hartle, R.E. (2001) Wave Driven Non-Linear Flow Oscillation for the 22-Year Solar Cycle. *Geophysical Research Letters*, **28**, 463-466.
https://doi.org/10.1029/2000GL012223

[30] Mayr, H.G, Mengel, J.G. and Chan, K.L. (1998) Equatorial Oscillations Maintained by Gravity Waves as Described with the Doppler Spread Parameterization: II. Heuristic Analysis. *Journal of Atmospheric and Solar-Terrestrial Physics*, **60**, 201-213.
https://doi.org/10.1016/S1364-6826(97)00123-5

[31] Imada, S., *et al.* (2020) Solar Cycle-Related Variation in Solar Differential Rotation and Meridional Flow in Solar Cycle 24. *Earth*, *Planets and Space*, **72**, Article No. 182. https://doi.org/10.1186/s40623-020-01314-y