Thank you for your time and effort. Your summary of my article is accurate. I see this article as a first step towards clarifying the 100 ka climate cycle, as well as better explaining the causes of geomagnetic variations such as magnetic reversals. Your comments indicate that a few of my arguments have failed to convince you of some key conclusions. I will address these individually below and rewrite the article to better clarify these issues once all final comments are in.

"… the correlations found in this study are not convincing and some physical concepts are misinterpreted. Many of the claims, e.g. P4L70-71, P4L73 (… almost cerntanly caused by the OI forcing), P5L91-92 need some proof."

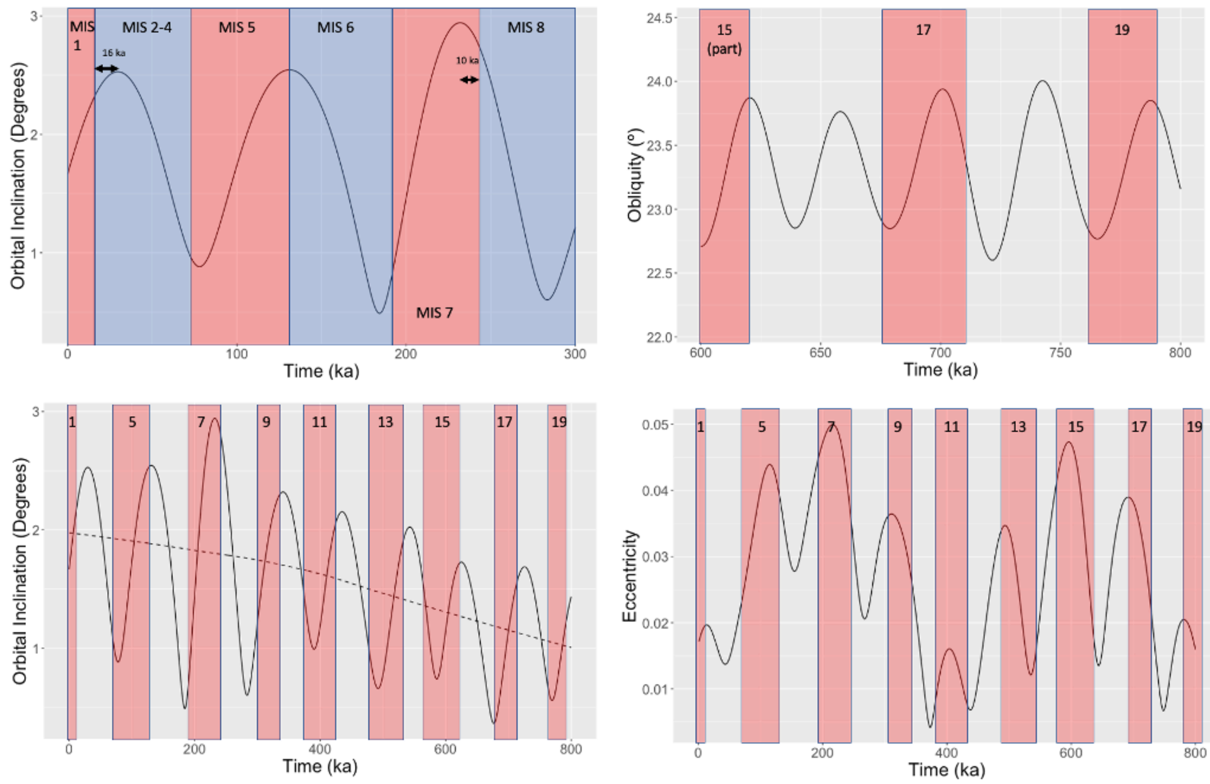
This comment goes to the heart of the paper, so I will try to make my reasoning clearer. I start by presenting the cross-correlations between OI, Obliquity and Eccentricity. These correlations are among the very best and clearest I've ever seen between time series, and I am therefore unclear whether these are the correlations you find unconvincing. The statistically significant, multi-cycle Obliquity and OI correlations indicate orbital forcings almost certainly – directly or indirectly - play a role in determining geomagnetic intensity variations. The blue dashed lines on the graphs indicate the 95% significance level, but the correlations are also significant at the 99% level (not shown on the graphs): there is therefore a <1% chance that the observed multi-cycle correlations are due to random chance. Especially convincing to me is that all orbital forcings show a good, significant correlation, because such builds confidence all three good correlations together happen by random chance is one in a million. I rule out sampling errors playing a significant role: the Laskar, 2004 and G&V curves are peer-reviewed, and therefore taken "as is". Which leaves the question of a lurking variable, that is some parameter X that also varies with all 3 orbital forcing frequencies (41, 100, 400 ka) as well as paleogeomagnetic intensity. But if such were the case than variable X is almost certainly orbitally-forced, indicating that paleogeomagnetic intensity variations indirectly are too, via intermediate parameter X. Therefore: the paleogeomagnetic variations are almost certainly directly or indirectly caused by OI, Obliquity, and Eccentricity variations. The fact that both commonly found orbital forcing signatures (Obliquity and Eccentricity) are clearly influential almost certainly means that the dominant 100 ka period is also caused by an orbital forcing. The fact that orbital inclination is the only orbital forcing to have a 100 ka period, coupled to its statistically significant cross correlation, means that the 100 ka period is almost certainly caused by OI-forcing. The rest of the article deals with the physical processes underlying OI forcing.

Orbital forcings therefore play a leading role in determining paleogeomagnetic intensity variations, so the next paragraphs deal with the plausible energy sources, which need to be large enough to influence/alter a geodynamo requiring 3.6-10 TW [Merrill et al., 1998; Verhoogen, 1980]. Ruling out cosmic forcings (evidently too small) leads to the conclusion that solar energy must be the orbital forcing source. Solar irradiation energy however can be ruled out: even if the G&V curve had a dominant 41 ka (Obliquity) period, one would be hard-pressed to imagine a process that converts solar irradiation energy – that doesn't penetrate through Earth's crust – into a large, geomagnetic power source that can vary geomagnetic intensity. But solar irradiation can additionally be ruled out as it insignificantly varies with orbital inclination (Viera), and therefore cannot explain the dominant 100 ka period. Fortunately, solar wind energy is more plausible:

- Orbitally-forced. OI variations demonstrably cause large solar wind intensity variations (see your point below)
- Interacts with the geomagnetic field (compresses and extends it on a daily basis) and therefore transfers energy to it.
- Has the right magnitude, i.e. 5 TW, and can be shown to vary between ~2 TW (OI = 3º) to ~ 10 TW (OI=0º), thereby fully bracketing the range estimated to power a geodynamo [Merrill et al., 1998; Verhoogen, 1980]

"1. Please use longer datasets for the paleomagnetism. 290ka is not sufficient to investigate periods of 100ka. PISO-1500 would be a better choice as it covers 1.5Ma. The correlations with orbital parameters would be far more convincing if longer time periods are covered."

I agree that an analysis over a longer period offers several advantages, but disagree 290 ka is insufficient. Going back longer than 800 ka suffers from numerous serious drawbacks, e.g. including the Brunhes–Matuyama magnetic reversal (780 ka) as well as including the period prior to the mid-Pleistocene transition after which the dominant climate (and geomagnetic) period shifted from 41 ka (Obliquity) to 100 ka (see PISO-1500; Channell, 2009, Fig. 3).



Interglacial (red) and glacial (blue) Marin Isotope Stage boundaries overlying Orbital Inclination (top and bottom left; Source: Muller & MacDonald, 1997; dashed line = 90% LOESS-smoothed average); Obliquity (top right) and Eccentricity (bottom right; Source: Lasker et al., 2004).

In addition, OI shows significant non-stationarity going back to 800 ka (see picture), while Eccentricity decreases to a minimum around 400 ka, all of which add significant complexity to the conclusions, without impacting the overall picture. Note that my article's conclusions are consistent with PISO-1500: cycle-average OI reaches a minimum around 780 ka, indicating the OC was consistently receiving higher amounts of solar wind energy around this time, indicating the OC was (over) heating, indicating the paleogeomagnetic intensity was reaching a local minimum (see below from Channell, 2009), thereby creating the correct environment for the Brunhes–Matuyama magnetic reversal. But all this is far beyond the scope of the article: the article needs to walk before future articles can run.

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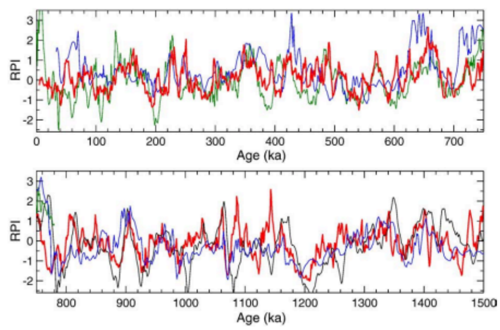
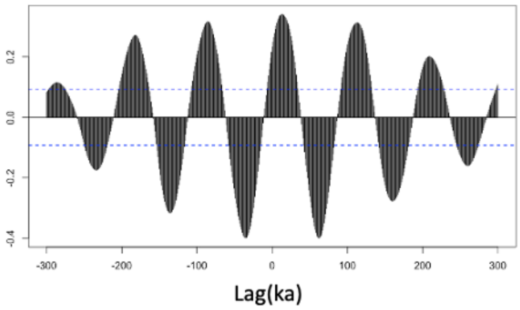


Fig. 5. The new paleointensity stack (PISO-1500, red) compared with the EPAPIS Pacific stack (black) (Yamazaki and Oda, 2005), with the inversion of magnetic anomaly data from the East Pacific Rise (green) (Gee et al., 2000) and the RPI record from ODP Leg 138 (blue) (Valet and Meynadier, 1993). In this plot, these records have been subtracted from their means and divided by their standard deviations. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

In addition Quinn et al.'s OI curve only extends back for 800 ka, but over this interval the multi-cycle cross correlation is good and significant.



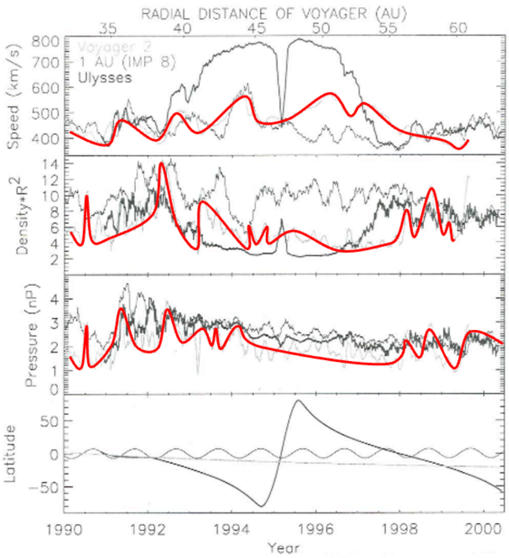
Additionally, G&V used a separate ∂18O paleotemperature proxy reference curve to normalize (age and value shift) the intervals older than 300 ka, which possibly makes comparisons of the post-300 ka to the pre-300 ka inappropriate (for now). Age uncertainty increases substantially for periods older than 40 ka, and for the less-documented MIS stages older than MIS 8. I therefore prefer the selected 290 ka period, as its correlations are statistically significant, and the subtle interplay between the orbital forcings readily explained, without overloading the reader with additional complexity.

"2. Solar wind explanation. The solar wind at 1 astronomical unit is essentially radial and nearly isotropic, it is not concentrated in the solar equatorial plane. Therefore, the Earth's small inclination changes would have negligible effect on the total intercepted solar wind energy. What matters far more are coronal mass ejections and the high speed solar wind streams."

I haven't been able to find any studies on Earth-incident solar wind variations during yearly, 11-year solar cycle or orbital time scales. The ones that deal with solar wind variations over the heliosphere invariably focus on its impact on something else of interest e.g. climate (Dessler, 1974; Herman & Goldberg, 1978) or the extent of the heliosphere, e.g.

Richardson, J. D., 2001, The solar wind: Probing the heliosphere with multiple spacecraft. In: The Outer Heliosphere: The Next Frontiers, Edited by K. Scherer, Horst Fichtner, Hans Jörg Fahr, and Eckart Marsch COSPAR Colloquiua Series, 11. Amsterdam: Pergamon Press, 2001., p.301

The solar wind model I employed was created from Richardson (2001), whose Fig. 1 deals with SW speed, density and pressure variations at 1 AU:



Note I added the red line over the Voyager data as its line is very faint (I have a B&W copy of the COSPAR book) and I presume the graph was originally in color. Richardson concludes: "***From solar minimum to solar maximum the latitudinal gradients of density and speed reverse so that at solar maximum speeds are higher near the solar equator, but solar cycle changes in the dynamic pressure occur at all solar latitudes. … During solar minimum, the speed and density decrease rapidly away from the solar equator. … The slow speed region is narrow enough that Earth's 7.25ºinclination produces significant speed effects***." Note Richardson projects the Voyager and Ulysses data back to 1 AU in order to compare the different datasets. Richardson claims that "***At solar minimum, low speeds and high densities are found only near the equator in a band with half-width of order 10º with a several degree transition region to the fast, low density wind which persists up to high latitudes"***, implying that Earth's Orbital inclination of 6°-9° relative to the solar equator (OI to the Invariable Plane of 0 – 3°) keeps it within the near equator band, simplifying things. The graph above shows that around the solar maximum (1992-1994) the solar wind Pressure (i.e. its energy) is roughly isotropic at 1 AU, but that during the solar minimum (1994-1998) that followed the IMP8 satellite (i.e. Earth) shows a higher solar wind pressure than the higher solar latitude Voyager or Ulysses. This is mainly due to the higher density of the SW in the solar equatorial plane. During the solar minimum Earth's SW density fluctuates between ~8 and ~12, with the higher value occurring when Earth passes through the solar equatorial plane (solar latitude 0°) and the lower values occurring when Earth's orbit reaches the higher (7.25°N and S) solar latitudes.

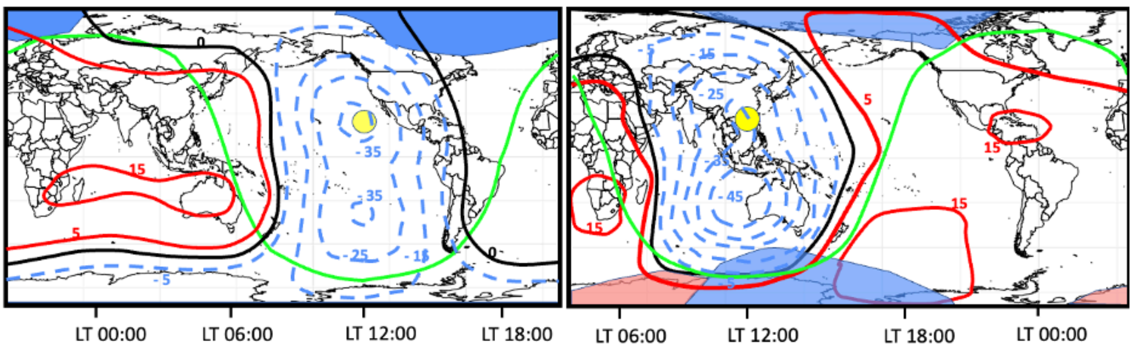
Using the work-energy principle Earth-incident solar wind power, Us, can be calculated as:

$$U_s = \pi\, R_M^2 \left(\frac{1}{2}\rho V_s^2 + \frac{{B_{IMF}}^2}{2\mu_0}\right) V_s \approx 6.4\, TW$$

where (assumed values between brackets) R_M is the magnetosphere radius (12 Earth radii), ρ the mass density of the solar wind, Vs the solar wind velocity (500 km/s), B_{IMF} the strength of the interplanetary magnetic field (10 nT), and μ_0 the vacuum magnetic permeability (1.26 10^{-6} H/m). Note that the second term between the round brackets, the incident magnetic energy of the IMF, is commonly ignored as its size is much smaller than the first term, which represents the solar wind momentum energy. When Earth is at 7.25° solar latitude a SW density of 8.10^{-21} $kg.m^{-3}$ results in a power of 6.4 TW. When passing through the solar equatorial plane however this increases to 9.6 TW ($\rho = 12.10^{-21}$ $kg.m^{-3}$). When Voyager left the 10° band around 1994 its observed SW density dropped to about 6.10^{-21} $kg.m^{-3}$, so at high OI values of ~3° (9° angle to the solar equator) the solar wind power is on the order of 2.5 TW. In a nutshell: when OI is low (OI = ~0°) the average Earth-incident SW power is significantly higher than when OI = ~3°

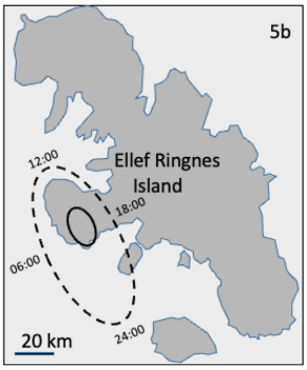
"3. Solar wind and changes in paleomagnetism. The paper claims that magnetic flux at the magnetopause must pass through the mantle before reaching the core; mantle is low conductivity, so it cannot regenerate the flux. Therefore, solar wind deformation of the field lines at the magnetopause somehow couples into the outer core. This is flawed - magnetopause currents are external, not internal. Internal field is the mag field generated by the geodynamo in the outer core, and external is induced by solar wind. The magnetic perturbations from the solar wind are generated outside the Earth, in the magnetosphere and ionosphere. These fields can be observed at the Earth's surface, but they are not transmitted through the mantle into the core as flux. Mantle is a poor conductor of the current and it protects the outer core from the direct penetration of the solar wind mag field. Magnetic variations from the magnetosphere could in theory induce small secondary currents in the mantle, but they are shallow and do not significantly affect the geodynamo. The opposite is true: The geomagnetic field shapes the magnetopause and drives how solar wind couples to Earth - solar wind produces external geomag variations which we can measure at the Earth's surface."

I understand the general gist of this comment, but feel it may be due to a confusion over jargon.



*Magnetic daily variation contours of the Solar Quiet total intensity (in nT) above the ionosphere at 20:30 UT (left) and 04:30 UT (right) derived from CHAMP satellite data (after Turner et al., 2007). Colored high latitude blobs represent observed high positive (red) and negative (blue) magnetic flux density changes. Yellow circle: solar direction; green line: daylight boundary. Note the undeformed field line (black line) near the ~LT 18:00 and ~LT06:00 meridians. (Turner, J. , Winch, D., Ivers, D., Stening, R., 2007, Regular daily variations in satellite magnetic total intensity data. Annales Geophysicae, **25**, 2167-2174.)*

The above pictures represent the magnetic daily variations above the ionosphere during a low activity (Solar Quiet) period. These geomagnetic variations are caused by the solar wind's charged particle deflection by the geomagnetic field via the Lorentz force: geomagnetic energy is converted to particle kinetic energy, thus locally lowering the geomagnetic field strength in the solar direction. The particles' kinetic energy is transferred to the magnetosphere as magnetic flux. Magnetic flux is defined as the surface integral of the normal component of the magnetic field, so locations where the field lines penetrate the Earth's surface at a high angle, that is the high-latitude region "sweet spots" where inclination > 70° (blue and red blobs above) experience greater EM flux variations than the equatorial regions (inclination ≈ 0°). On a schematic: any movement of the geomagnetic field lines ($\partial B/\partial t$) represents the magnetic flux energy that is transferred. A small part of this flux energy is absorbed by the ionosphere and induces currents that attempt to undo (Lenz law) the magnetic flux variations, but what's measured at Earth's surface is a combination of the two.



Daily path of the North Magnetic Pole (NMP) in 1991 (after Geological Survey of Canada 2008): small solid ellipse represents "quiet" days of low solar wind; large dashed ellipse represents the path during more active days.

The ionospheric currents cannot completely "undo" the magnetic flux variations, as is evidenced by the above picture: the solar wind "pushes" the magnetic field lines, in this case the NMP away from the solar direction, causing magnetic flux at high latitudes. The induced ionospheric currents/fields cause (small) diminishment of the solar wind generated magnetic flux, but cannot completely cancel it (efficiency < 100%). Solar wind generated magnetic flux therefore enters solid Earth, where it is commonly assumed it is quickly absorbed by Earth's Mantle, based on commonly assumed skin depth models. E.g. Banerdt, 2014, on deep EM probing of planets:

> The effective penetration depth for EM waves is a strong function of frequency and resistivity. The EM skin depth (in meters) is given by $\delta = 500/\sigma^{1/2} f^{1/2}$, where σ is the conductivity (S/m) and f is the frequency (Hz). This relation

Ott, 2009 and Schelkunoff, 1943, who formulate more complex skin depth models whereby conductivity is a function of frequency, but even Banerdt agrees that low frequencies on the order of 10^{-5} Hz, i.e. the EM wave pulse generated by the solar wind, can be used to image the Lower Mantle. That is to say even under Banerdt's overly conservative skin depth model, some solar wind generated magnetic flux makes it to the outer core, thereby establishing a route for solar wind generated EM flux to reach the OC.

I explain most of this in the text, but in summary Ott indicates magnetic flux absorption is a function of shield conductivity (σ_r) and shield magnetic permeability (μ_r), both which vary as a function of frequency, and that assuming a static conductivity model and constant magnetic permeability – as Banerdt does - are inappropriate simplifications when determining the Mantle's absorption of electromagnetic waves with frequencies below 1 kHz, as the electromagnetic properties of Earth's layers - μ_r and σ_r - vary greatly with frequency [Ott, 2009; Schelkunoff, 1943]. Ott claims experimental data suggest that absorption by non-magnetic shields is relatively insignificant for frequencies below 1 kHz (see graph from Ott below).

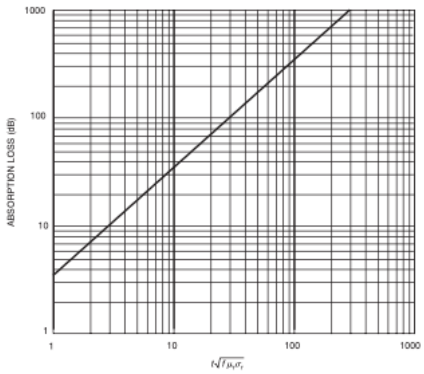


FIGURE 6-8. Universal absorption loss curve.

A final point I would like to make is that in the solar quiet pictures above, you can see the geomagnetic field energy that was consumed by the solar wind incidence to the west of Mexico at 20:30 UT has been resupplied by 04:30, that is to say some energy source resupplied the magnetic flux energy and restored the geomagnetic field back to its normal, undeformed values. This restorative geomagnetic flux energy must have been generated in the outer core by the geodynamo and have travelled upwards through the Mantle. If restorative flux energy can travel up through the Mantle to the Magnetopause the solar wind generated flux energy can travel down through the Mantle to the OC. Physical theory and observations therefore overwhelmingly point to the fact that non-magnetic shields such as the Mantle do not absorb significant amounts of low frequency EM energy.