Dear Stephen Meyers,

Thank you very much for your detailed review.

Below we will reply to the comments.

… I would like to bring the attention of the authors to a recently published study by Ma et al. (2017), which provides geologic evidence confirming the chaotic behavior of the Solar System, through the identification of a chaotic resonance transition during the Coniacian (~85-87 Ma) …

The Ma et al. (2017) manuscript was not published at the time when this manuscript was submitted but will be considered in the revised version.

My major recommendation for revision of the present CPD manuscript is to follow the quantitative recipe that is outlined in Ma et al. (2017): (1) run the Astrochron R-script to test for the expected amplitude modulations in the 405 ka tuned data and (2) construct an analysis similar to that in Table 1 of Ma et al. (2017), to eliminate the possibility that changes in sedimentation rate (including hiatus) are influencing the observed modulation patterns.

Regarding 1) - We have compiled a new figure (Fig. 1 below, also see reply to Hilgen review) with the statistical analysis on the XRF Fe intensity data from ODP 1258, 1262, and 1263. We follow the approach of Zeeden et al. (2015) which is similar to the Ma et al. 2017 recipe: filtering out the short eccentricity cycle (100-kyr) using a broad bandpass filter (0.004 to 0.016 cycles/kyr; 250-62.5 kyr per cycle; Tukey window) and subsequently making a Hilbert transform to extract the AM using the *Astrochron* software package (Meyers 2015) for Site 1258 and 1263 data. As a basic age model we used the 405-kyr age model as given in table 46 of the submitted dataset. The resulting 405-kyr AM of the XRF Fe intensity data are the plotted against the La2004, La2010, and La2011 orbital solutions (Fig. 1 above, also see reply to Hilgen review).

Regarding 2) – Table 1 of Ma et al. (2017) is about radioisotopic anchors used for the Libsack astrochronology. Our record does not include ash layers for which we could do a similar analysis. Therefore, it is not clear to us why the reviewer is suggesting this approach. A similar table for calcareous nannofossil events or magnetostratigraphy would be rather complex and would in no way be helpful in identifying hiatuses or jumps in sedimentation rate also as these zones do not resolve time in suitable resolution if compared to cyclostratigraphy. Please be aware that we are using multiple records too from two different regions to ensure we are dealing with a complete record. We made clear in the manuscript that a single site or region record potentially could include gaps and/or condensed sections that could only be detected if compared to another record. Deriving errors from calcareous nannofossil datums at different site is difficult because they are not perfectly synchronous between Site 1258 and Leg 208 sites. Even between Leg 208 sites some events are not accurately synchronous probably due to sampling and / or depth related (dissolution etc.) issues. It is also in the nature of magnetostratigraphy with each site exhibiting slightly different results that error analysis is not straight. We could for example imagine that a second Libsack core (Ma et al. 2017) would also yield slightly different ages for ash layers. Thus we refrain from compiling a table like in Ma et al. 2017 as it will not provide better constraints on the data as already in the extensive dataset from multiple records presented in the manuscript.

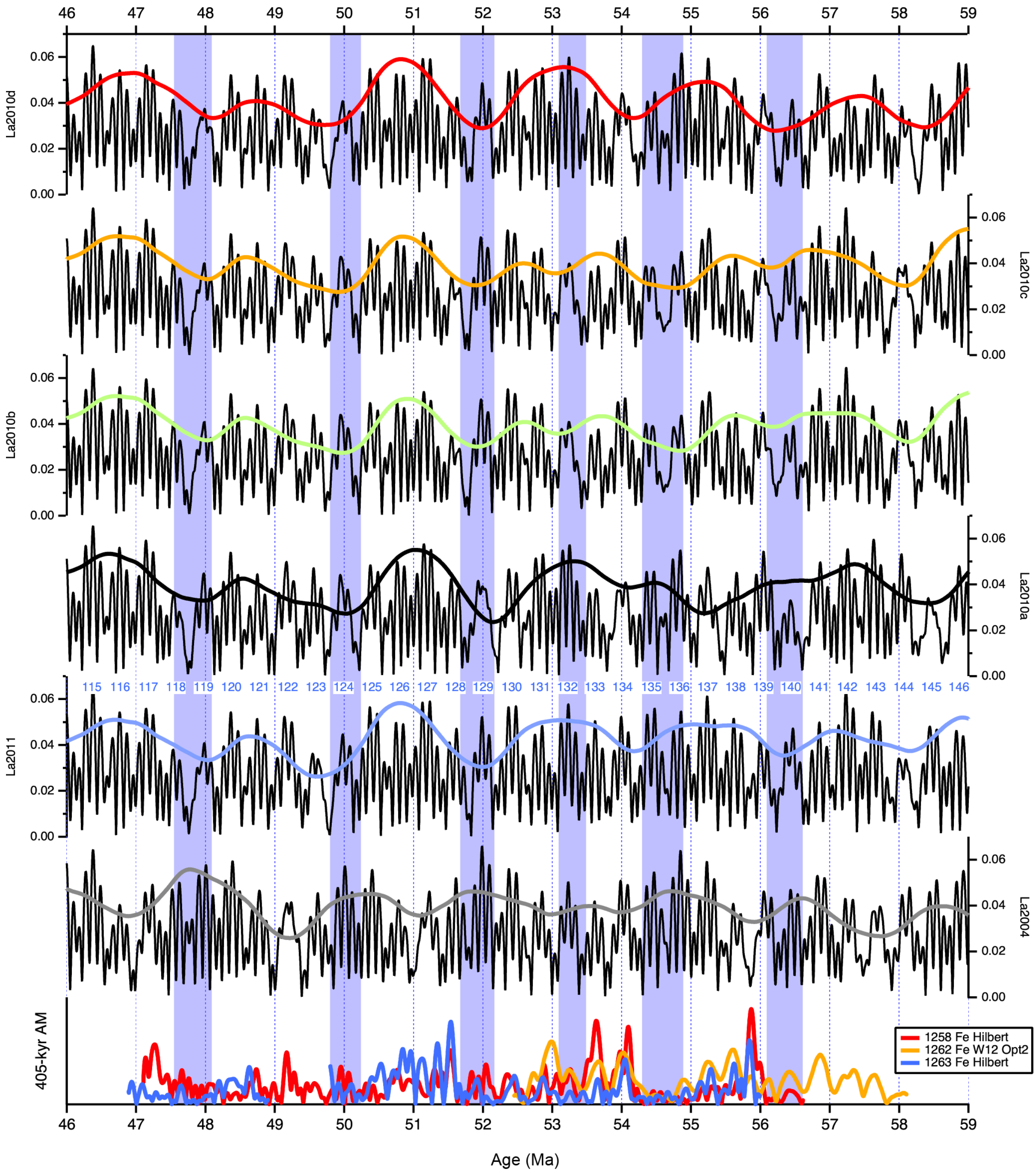

Figure 1 – Comparison of the amplitude modulation (AM) of the short eccentricity cycle between the La2004, La2010, and La2011 orbital solutions and Fe intensity data from ODP Sites 1258 (red), 1262 (orange) and 1263 (blue). For the orbital solutions we also plotted the 405-kyr AM. The short eccentricity AM of Sites 1258, 1262 and 1263 Fe intensity data are plotted on the 405-kyr scale model (Table 46 of the submitted manuscript). The very long eccentricity minima are highlighted by light blue bars in the orbital solutions and the Fe intensity data. Statistical and visual recognition of cycle pattern suggest that the La2010b and La2010c solutions are most consistent with the geological data.

In terms of testing for a chaotic resonance transition, it would be ideal to apply this approach to a floating 405 ka time scale that is not directly anchored to a theoretical astronomical solution, to avoid circular reasoning; if feasible, this can be included as a supplementary analysis. In addition to verifying the presence of a chaotic resonance transition – if present – these analyses provide more rigorous statistical grounds for selecting the appropriate theoretical model for short eccentricity tuning.

We have done so, as described in the reply to Hilgen review, and will include this in the revised manuscript.

An example of the power spectrum integration approach, which is central to the Ma et al. (2017) methodology, is provided in the Astrochron R-script below. Please run this script to produce a summary figure illustrating the characteristic "grand cycles" that are expressed in the amplitude (and power) modulation of the short eccentricity terms. The resultant plots provide a fingerprint of the grand cycles associated with the different theoretical astronomical solutions, for comparison with the Walvis Ridge and Demerara Rise data. For example, note the change in the character of the grand cycles in the La2010b solution at ~50 Ma (panel b), and also, the unusual behavior of the La2004 solution at ~52.5 Ma (panel a).

We applied the script and will add the following figure (Fig. 2 in this reply) to the revised manuscript supplement.

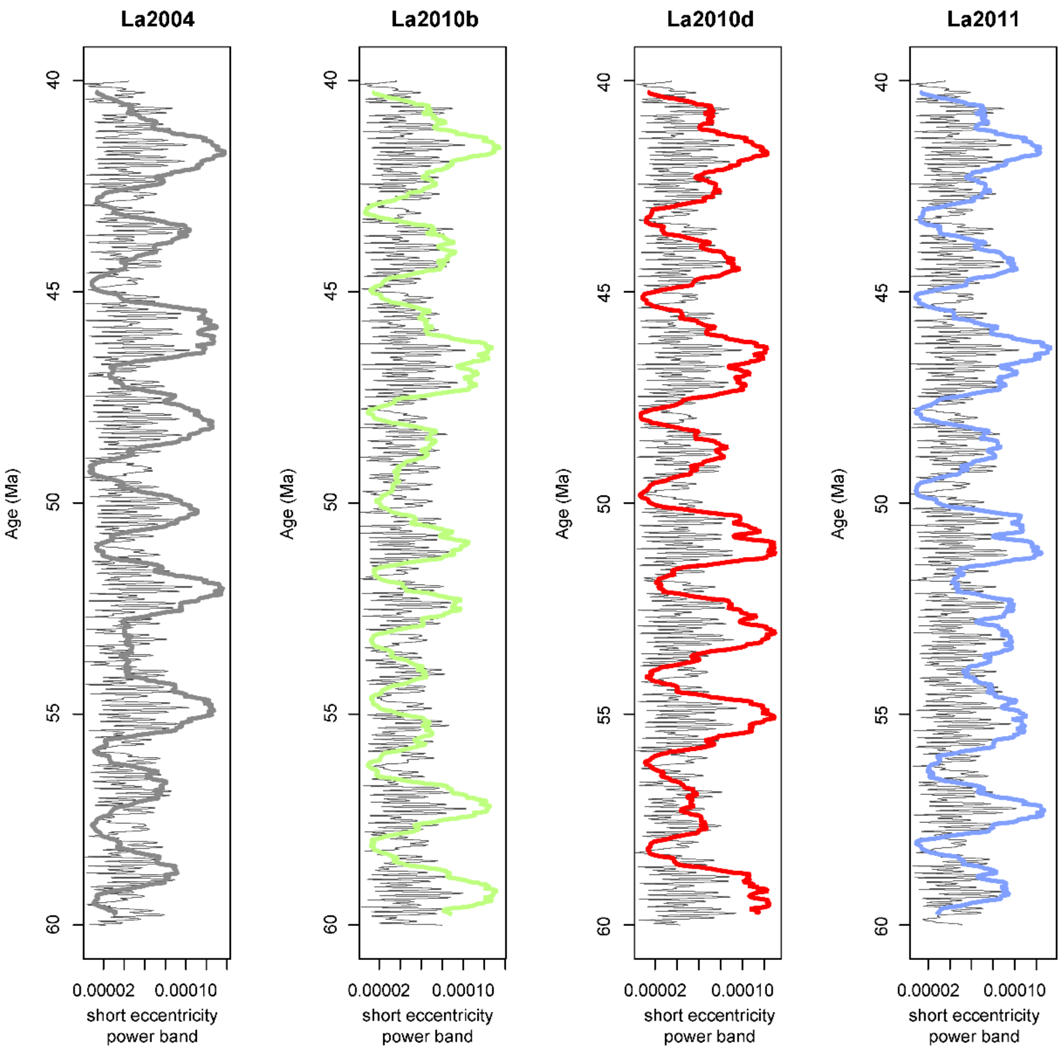

Figure 2 - Short eccentricity band power for La2004, La2010b, La2010d and La2011 extracted using the *Astrochron* software (Meyers 2014) according to Ma et al. (2017) from 40 to 60 Ma. The results are similar to those plotted in Figure 1 above (from Westerhold et al. 2012). The La2010b solution clearly shows the transition from libration to circulation and back between 52 and 55 Ma. In contrast La2010d and La2011 solutions do not show the transition. La2004 solution also does not show the transition, but an unusual behavior from 53 to 54 Ma. Please note that the AM of La2010 and La2011 solutions are very similar to 50 Ma but diverge thereafter. The La2004 solution AM is similar to the La2010 and La2011 up to 45 Ma, in times older that than 45 Ma the AM significantly diverge (as discussed in Westerhold et al. 2012).

The proposed link between chaotic orbital behavior and changes in ocean spreading rate (conclusion 3 noted above) is the most speculative. If it is to be included in the manuscript in a meaningful manner, I believe it is necessary to provide a more complete description of the physical mechanism by which it is manifested, either qualitatively (how does orbital behavior impact mantle flow, and how would a chaotic transition thus be expressed as an increase in spreading rates?), or even better quantitatively through modeling. Of course, correlation is not proof of causation, but if the orbital behaviors can be reasonably demonstrated to have the appropriate order-of-magnitude effect on mantle flow and plate reorganization, this would be an important discovery.

Our manuscript is data rich. And includes surprisingly new results which cannot all be extensively presented in a single manuscript. The reviewer asks: *how does orbital behavior impact mantle flow, and how would a chaotic transition thus be expressed as an increase in spreading rates?, or even better quantitatively through modeling.*

We argue here that these are perfect questions for future research projects and modeling studies that should address and test our new findings. We definitely agree that correlation is not a proof of causation.

The Ma et al. 2017 paper argues that Ocean Anoxic Event 3 (OAE 3) might be mechanistically related to the transition. They speculate that "*Such a resonance transition would permit positive reinforcement of eccentricity- and obliquity-modulated seasonality, allowing for a more pronounced impact of astronomical forcing on palaeoceanography*." We think this is also very speculative and would require modeling to be rigorously tested.

Setting up a model for the complex and chaotic mantel flow is highly sophisticated and should be done by exerts in that field, not us. We hope to give some inspiration to the modeling community to test our hypothesis. This will require a new kind of collaboration between dynamic mantel flow modeling and astronomy, something to our knowledge not undertaken before.

In conclusion, I would like to reiterate that the data production and assimilation campaign that is the foundation of this study is an impressive effort, which is no doubt a tribute to the expertise of this research group, and the decades of careful work that they have conducted on the topic of Eocene astrochronology. Further, I believe that these new records will yield considerable insight into astronomical forcing during the Ypresian, a time of great interest due to the numerous hyperthermal events that are present and the overall warm climate state. It is my hope that the application of the statistical methodologies outlined in this review help to clarify and strengthen the hypothesis testing, and thus reduce the ambiguity associated with multiple plausible interpretations of the data.

We agree that the focus of the manuscript is the very complex data synthesis. In the revised version we will include more rigorous statistical testing as outline above and in the reply to reviewer Frits Hilgen. We hope that our compilation of published and new data will be basis for insightful research in the Ypresian to understand climate dynamics in a warm world with elevated pCO_2.

Additional comments

Page 11, lines 4-5: Here is it noted that "Because of higher sedimentation rates than observed at Leg 208 sites, cyclicity in the Site 1258 XRF Fe data is mainly precession related with less pronounced modulation by eccentricity." This statement requires further explanation; as written it would suggest that sedimentation rate changes may impose amplitude modulation upon precession (and short eccentricity?) as an artifact, which could complicate the assessment of the long term "grand cycles".

The sentence is not referring to sedimentation rate changes but varying sedimentation rates at different sites. Higher sedimentation rates in the order of 3 to 5 cm / kyr lead to pronounced precession cycle recordings. Slower sedimentation rates tend to amplify the modulation of precession cycles, thus eccentricity. Secondly, as stated in Westerhold & Röhl (2009), the XRF data from 1258 show strong eccentricity-modulated precession cycles, meaning that precession cycles dominate (due to the relatively high sedimentation rates), but these cycles are clearly modulated by eccentricity. Compared to lower sedimentation rate sites with 1 to 2 cm /kyr the modulation of eccentricity is less pronounced in the XRF data. We will clarify this in the revised version modifying Page 11, lines 4-5.

Page 11, line 19; Figure S9 caption; Figure S11 caption: Please specify the details of the detrending approach utilized, so that it can be replicated in future work. Note that Astrochron includes several functions for detrending that may be of utility here (e.g., functions 'noLow' and 'noKernel').

The full sentence is as follows "*Published benthic and bulk stable isotope data were combined for Leg 208 and Site 1258 (Fig. 2 and S7), plotted on the 1263 rmcd and detrended for long term trends (Fig. S9)*".

Figure S9 caption says "*Second, a long-term average (thick grey) was defined graphically to avoid removing the apparent 405-kyr cycle*". The bulk and benthic isotope data have been linearly interpolated at 2 cm spacing. Then the data were smoothed using the IGOR Pro smooth operation using binomial (Gaussian) smoothing and 30001 points in the smoothing window. We smooth the data using a Gaussian filter and then subtract the smoothed curve from the original data to form a residual curve. We chose a Gaussian filter because it weights the center of the smoothing window more than the flanks (as opposed to a Boxcar filter which weights all values within the smoothing window equally). The smoothing factor (e.g., 1000, 10000, 30000) dictates how wide the effective window is. The wider the window, the less weighting is applied to the center and the significant contributions to the smoothed value extend further out from the center. The choice of smoothing number is subjective; selected by the operator through multiple trials to best eliminate one-off data shifts while including cyclic signals. Low smoothing numbers tend to accentuate high frequency signals in the residual while larger smoothing numbers include more low frequency power.

We will make sure to add these details to the revised manuscript.

Page 18, line 13: Please note the study by Laurin et al. (2016), which provides additional independent confirmation of the eccentricity pacing of these hyperthermals.

We will add the reference to the revised version (Laurin, J., Meyers, S.R., Galeotti, S., and Lanci, L. (2016). Frequency modulation reveals the phasing of orbital eccentricity during Cretaceous Oceanic Anoxic Event II and the Eocene hyperthermals. Earth and Planetary Science Letters 442, p. 143-156)

Figure S3 (item 1). It is excellent to see that this study evaluates the reproducibility of the XRF Fe data, which is standard practice when presenting most geochemical results, but often ignored in XRF scanning studies….

There might be a misunderstanding here. Figure S3 shows the intercalibration for Fe intensity data obtained from different generations of XRF core scanners and their distinct hardware for Site 1262 and 1267. NOT reproducibility. This was done to be able to plot all data on the same y-axis. Thus the extended comment in this paragraph is not really relevant for the study.

Figure S3 (item 2): It is necessary to include a similar analysis and plot for the iron data from Site 1263.

See above. The intercalibration is only needed to plot the data on the same y-axis and be able to analyze the full data set for time series analysis. It will not change or improve the results of the manuscript.

Figure S12: While the proposed match between the theoretical astronomical solution and the benthic carbon isotope data seems plausible throughout much of the record, the interval from 51-52 Ma shows a response that is opposite to what theory predicts. This requires some further comment in the manuscript.

The interval mentioned is around ~260 rmcd at Site 1263 where due to a major shift in $\delta^{13}C$ two tuning options identifying two or three 405 kyr cycles were proposed by Lauretano et al. (2016). In chapter *4.1 How many 405-kyr cycles represent Chron C23?* this particular interval is discussed in detail. The data shown in Figure S12 are detrended compiled benthic stable isotope data. The major carbon shift at ~260 rmcd at Site 1263 complicates the tuning procedure. But taking other data into account (bulk carbon isotopes, XRF Fe intensities; see Figure 3 of the submitted manuscript) we are confident about the quality of the tuning in this interval.

In the revised manuscript we will add a critical comment to chapter 4.1 dealing with the unusual carbon isotope data pattern in the 51 to 52 Ma interval.