Clim. Past Discuss.,
doi:10.5194/cp-2017-15-RC2, 2017

Climate of the Past
Discussions
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Interactive comment on “Astronomical Calibration of the Ypresian Time Scale: Implications for Seafloor Spreading Rates and the Chaotic Behaviour of the Solar System?” *by* Thomas Westerhold et al.

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Received and published: 16 March 2017

The manuscript "Astronomical Calibration of the Ypresian Time Scale: Implications for Seafloor Spreading Rates and the Chaotic Behaviour of the Solar System?" presents a complete eccentricity-based astronomical tuning of the Ypresian time scale (47.8-56.0 Ma), through the synthesis of new and published data from Demerara Rise (ODP Site 1258) and the Walvis Ridge (ODP Sites 1262, 1263, 1265, 1267). The data production and assimilation campaign that is the foundation of this study is an impressive effort, and well documented in the manuscript. The results are taken to (1) resolve a controversy about the appropriate astronomical tuning through the interval (the question of how many 405 ka cycles are in magnetochron C23, and the identification of the correct theoretical model for short eccentricity tuning), (2) provide confirmation of the chaotic behavior of the Solar System that has been proposed based on theoretical models (e.g., Laskar et al., 1989), and (3) identify an increase in ocean spreading rate between 51-52.5 Ma that is interpreted to be linked to chaotic orbital behavior, through an influence on dynamic mantle flow.

These conclusions embody a series of hypotheses that have been tested with varying degrees of rigor. Central to this study is the identification of the correct theoretical eccentricity model (Laskar et al., 2004, 2011a, 2011b), and related to this, confirmation of the chaotic behavior of the Solar System. 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). Of relevance to the present CPD manuscript, Ma et al. (2017) present a framework of statistical tests that provide a rigorous basis for the identification of chaotic resonance transitions. This is achieved through quantitative evaluation of the amplitude modulation of a number of carrier signals that express the secular resonance (see Ma et al. sections "Data analysis" and "Approaches for quantifying the (s4-s3)-(g4-g3) secular resonance", and the supplementary Astrochron R-script provided in that paper; Meyers, 2014), and by leveraging available independent time control (e.g., radioisotopic data and their uncertainties, including correlation uncertainties) to eliminate potential artifacts from changes in sedimentation rate (see Table 1 of Ma et al., and the section "Anchoring the floating astrochronology with radioisotopic data").

Therefore, 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. 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.

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).

```
# ———- BEGIN Astrochron script ———-

# compare short eccentricity modulations ("grand cycles") from La2004, # La2010b,
La2010d, La2011

library(astrochron);

la04=getLaskar("la04");

la10b=getLaskar("la10b");

la10d=getLaskar("la10d");

la11=getLaskar("la11");
```

```
# set plotAll=T if you want to view the progress of each function graphically # (this is
slower). set plotAll=F if you simply want to display the final summary plot.

plotAll=F;

if(!plotAll) plot2=0;

if(plotAll) plot2=3;

# extract interval from 40-60 Ma and interpolate to 2.5 ka

la04ecc=iso(linterp(cb(la04[,1],la04[,4]),dt=2.5,genplot=plotAll),xmin=40000,
xmax=60000,genplot=plotAll);

la10becc=iso(linterp(cb(la10b[,1],la10b[,2]),dt=2.5,genplot=plotAll),xmin=40000,
xmax=60000,genplot=plotAll);

la10decc=iso(linterp(cb(la10d[,1],la10d[,2]),dt=2.5,genplot=plotAll),xmin=40000,
xmax=60000, genplot=plotAll);

la11ecc=iso(linterp(cb(la11[,1],la11[,2]),dt=2.5,genplot=plotAll),xmin=40000,
xmax=60000, genplot=plotAll);

# compute evolutive power spectra, and conduct short eccentricity integrations

pwr_la04=eha(la04ecc,win=500,fmax=.1,output=2,pl=1,pad=5000,genplot=plot2,
ydir=-1,xlab="Frequency (cycles/ka)",ylab="Age (ka)");

integrate_ecc_la04=integratePower(pwr_la04,flow=0.007,fhigh=0.012,npts=201,
pad=5000,ln=T, ydir=-1,genplot=plotAll);

pwr_la10b=eha(la10becc,win=500,fmax=.1,output=2,pl=1,pad=5000,genplot=plot2,
ydir=-1,xlab="Frequency (cycles/ka)",ylab="Age (ka)");

integrate_ecc_la10b=integratePower(pwr_la10b,flow=0.007,fhigh=0.012,npts=201,
pad=5000,ln=T, ydir=-1,genplot=plotAll);
```

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pwr_la10d=eha(la10decc,win=500,fmax=.1,output=2,pl=1,pad=5000,genplot=plot2,
ydir=-1,xlab="Frequency (cycles/ka)",ylab="Age (ka)");
integrate_ecc_la10d=integratePower(pwr_la10d,flow=0.007,fhigh=0.012,npts=201,
pad=5000,ln=T, ydir=-1,genplot=plotAll);
pwr_la11=eha(la11ecc,win=500,fmax=.1,output=2,pl=1,pad=5000,genplot=plot2,
ydir=-1,xlab="Frequency (cycles/ka)",ylab="Age (ka)");
integrate_ecc_la11=integratePower(pwr_la11,flow=0.007,fhigh=0.012,npts=201,
pad=5000,ln=T, ydir=-1,genplot=plotAll);
pl(r=1,c=4);
plot(integrate_ecc_la04[,2],integrate_ecc_la04[,1],type="l",ylim=c(60000,40000),
ylab="Time (ka)",xlab="La2004 Short Ecc. Power");
mtext("(a)",line=1);
plot(integrate_ecc_la10b[,2],integrate_ecc_la10b[,1],type="l",ylim=c(60000,40000),
ylab="Time (ka)",xlab="La2010b Short Ecc. Power");
mtext("(b)",line=1);
plot(integrate_ecc_la10d[,2],integrate_ecc_la10d[,1],type="l",ylim=c(60000,40000),
ylab="Time (ka)",xlab="La2010d Short Ecc. Power");
mtext("(c)",line=1);
plot(integrate_ecc_la11[,2],integrate_ecc_la11[,1],type="l",ylim=c(60000,40000),
ylab="Time (ka)",xlab="La2011 Short Ecc. Power");
mtext("(d)",line=1);
# ———- END Astrochron script ———-
```

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.

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.

Outlined below are a number of additional comments that are referenced to the pages and line numbers in the CPD manuscript.

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".

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’).

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.

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.

The results from Site 1267 look excellent, but an r-squared value of 0.09 associated with the Site 1262 XRF Fe data sets indicates a surprisingly poor correlation. Please estimate the significance of the correlations (specify the p-value), and note that this should be done in a manner that accounts for autocorrelation in the data series, such as the phase randomized surrogate approach of Ebisuzaki (1997). The Ebisuzaki method has been adapted and included in Astrochron as the function ‘surrogateCor’ (Baddouh et al, 2016). Given that only 9% of the variance is shared between the two Site 1262 XRF Fe data sets, the implications of this for the conclusions of the study need further discussion (approximately 38% of the data comes from the first scanning study, and 62% from the second).

More generally, I would like to encourage the adoption of an XRF data reporting approach that quantifies instrument stability (e.g., see Figure A.1 of Ma et al, 2014), and reproducibility based on duplicate analyses (e.g., see Figure A.2 and Table A.1 of Ma et al., 2014).

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

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.

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