The Pacemaker of the Chandler Wobble

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The Chandler Wobble is one of the largest circumannual periodic or quasi-periodic variations in the earth's orientation. After over a century of searching for its forcing, it was found to be caused by atmospheric circulation and induced ocean circulation and pressure. The question of why there should be such forcing from the atmosphere has remained open. Variations in earth-sun distance cause this forcing to the atmosphere and thence the ocean. Analysis of earth-sun distance, earth's orientation, and atmospheric winds shows a coherent relationship between the atmosphere and earth orientation at just those periods expected from earth-sun distance variation. As this is a general mechanism, it can be used in examining regular climatic variations on a wide range of periods and for climate parameters other than the earth's orientation.

1. Introduction

The Chandler Wobble (CW) is a small variation in the orientation of the earth's rotational axis [*Chandler*, 1891]. It has a period near 433 days [*Liao and Zhou*, 2004] (0.8435 cycles per year, 0.0023095 cycles per day). Some source of energy for the Chandler Wobble must exist because it dies out on a time scale of decades [*Munk and MacDonald*, 1960] if energy is not continuingly added. *Gross* [2000] found that atmosphere-ocean forcing on the earth's rotation, computed in an ocean general circulation model driven by observed meteorological parameters, provided that forcing. [*O'Connor et al.*, 2000] also found wind forcing of the ocean to drive the pole tide. This source was questioned [*Wunsch*, 2001] partly on the grounds that the ocean was displaying a very narrow band response, but there was no reason to believe that the forcing itself was narrow band.

I suggest that the atmosphere-ocean variability near the Chandler Wobble period, among others, is paced by variation in earth-sun distance. The earth-sun distance, in addition to annual and semi-annual variations due to the elliptical shape of the earth's orbit, varies due to perturbations from the moon (29.53 day period and others), Venus (292, 584, 417, 1455, ... days), and Jupiter (399, 199, 439, 489, ... days). The size of these variations is small, the largest being the 29.53 day lunar synodic period ($31*10^{-6}$ Astronomical Units), amounting to approximately 0.08 W/m^2 on a plane perpendicular to the sun at the top of the atmosphere. See Table 1 for more precise periods and the amplitudes of distance variations corresponding to them.

Horizons [*Giorgini et al.*, 1996] was used to provided 6-hourly earth-sun distance and osculating elements for 1 Jan 1962 00 UTC through 31 Dec 2008 18 UTC. Table 1 was derived by harmonic analysis of those data at precise frequencies to determine purely cyclic variations in the earth-sun distance. The leading terms are, of course, the annual and semi-annual cycles from the elliptical orbit. Following this, however, are perturbations in Earth-Sun distance due to the moon, Venus, and Jupiter.

Note that the orbital elements are not precisely locked to the periods given. The osculating (instantaneous) orbital elements vary; the osculating year varies from 364 to 366 days, for instance [*Giorgini et al.*, 1996]. Consequently, there are residuals near the annual period. But they are far smaller than the main line. The anomalistic year, 365.259635 days [*Observatory and Observatory*, 2001], is the period between successive perihelia. This has been found to be the appropriate period for climate temperature analysis rather than the tropical (vernal equinox to vernal equinox) year [*Thomson*, 1995]. As we will be drawing the conclusion that earth-sun distance is important, even for small variations, the anomalistic year is the self-consistent one to use here.

Previous analyses of orbital variation at relatively high frequency (high compared to, e.g., Milankovitch periods [*Milankovich*, 1941]) have used annual average orbital parameters [*Borisenkov et al.*, 1985; *Loutre et al.*, 1992], precluding them from examining periods shorter than 2 years and aliasing some of the periods examined here. Also, those works were examining the earth's tilt, rather than earth-sun distance. Gravitational torques have been examined previously as the main driver of the Chandler Wobble and rejected [*Munk and MacDonald*, 1960; *Lambeck*, 1980], which means only non-gravitational external forces, such as earth-sun distance, force Chandler Wobble at these periods, if any external sources do.

The ocean pressure and circulation forcing found by *Gross* [2000] itself required an atmospheric forcing (in pressure and/or wind stresses). And [*O'Connor et al.*, 2000] found that wind stresses were sufficient to drive the pole tide, so we examine the wind speeds and surface pressure. The 2 meter surface air temperature is included as well. The time period used is 1962-2008, beginning when daily International Earth Rotation Service (IERS) observations [*Gambis*, 2004] are first available, using the NCEP/NCAR (National Centers for Environmental Prediction / National Center for Atmospheric Research) Reanalysis output [*Kalnay et al.*, 1996].

In a meteorological reanalysis, observational data such as satellite observations, radiosondes, ship observations, and so on are assimilated by a weather forecast model and assimilation system. Such systems typically have a very simple understanding of the earth's orbit. For the NCEP/NCAR Reanalysis, the system considers the earth's orbit to be a fixed perfect ellipse with the sun exactly at one focus, and with the earth's tilt to be constant [*Kalnay et al.*, 1996]. Important for our consideration is that if orbital periods appear in the reanalysis output, they must be there because either they are present in the data which were assimilated, or noise which just happens to have exactly the periods expected from orbital consideration.

We examine meteorological time series harmonically, for each grid point in the analysis model (T62, approximately 200 km spacing). *Gross* [2000] and [*O'Connor et al.*, 2000] used this data set as well. Both used monthly average meteorological forcing. We will use full time resolution of the original meteorological reanalysis – 6 hourly information. This avoids the aliasing that calendar month averaging produces. Calendar month averaging aliases a unit amplitude at the lunar synodic month's period to 0.28 amplitude at 33.3 months, 0.004 at 18.9 months, 0.009 at 8.8 months, and 0.004 at 7.3 months. A unit amplitude at the sidereal month is aliased to 0.1 amplitude at 8.8 months and 0.002 at 33.6 months (n.b. there are signs of this in [*O'Connor et al.*, 2000]). A lunar synodic period has been observed previously in MSU atmospheric temperatures [*Balling and Cerveny*, 1995; *Shaffer et al.*, 1997], and earth-sun distance rejected [*Balling and Cerveny*, 1995], or re-considered inconclusively [*Shaffer et al.*, 1997] as a source for the signal.

Latitude band-averaging showed the lunar signal in MSU temperatures better than simply averaging over the globe [*Shaffer et al.*, 1997]. Figure 1 shows the amplitudes for harmonics in surface pressure at the orbital periods for latitude band averaging for each latitude in the reanalysis. We see the same general pattern as previously found [*Shaffer et al.*, 1997] – polar amplification of the signal. Further, the amplitudes are generally mutually correlated, there being, for instance, a zone of generally high amplitude oscillations at all frequencies around 30 N. Similar patterns are observed in u, v, and 2 meter air temperature.

The second step is to consider whether the earth's rotation variations are coherent with these meteorological variations. If the reanalysis were erroneous in some way that tended to produce large amplitude variations at these orbital frequencies, even though there is no reason for it to do so, variations at these periods nevertheless have no reason at all to be coherent with the earth's orientation variations. The earth's orientation's known periodic variations near annual period are the CW itself, annual and semi-annual, and a 292 day period found in some investigations [*Rudnick*, 1956]. 417, 489, 584 day periods and so forth have no reason to be present in the IERS data, much less to be coherent with meteorological fields, unless there is in fact a causal connection between the two.

Figure 2 shows the coherence (computed using *Paillard et al.* [1996]) between the northward velocity along latitude 79 N and the x deviations of the earth's orientation. Three curves are shown for each orientation. The first is coherence using all data. The second is coherence of the latitude average after removing the linear trend and first 6 annual harmonics. The third is coherence after the table 1 orbital periods above are extracted from the data. There are three senses for change in coherence to occur after extracting the orbital periods: 1) No change, which indicates that the period has negligible amplitude, or at least negligible effect on the coherence between the meteorological parameter and the rotation parameter. 2) Large decrease in the coherence, which indicates that the coherence is due to the narrow band orbital forcing(s) that were removed. 3) And large increase in coherence. This last looks odd. But in general, a spectrum includes both narrow-band components and broad-band. Computed coherence will be lowered when both narrow and broad band components are present and important. With spectral bleeding, aliasing, and window effects, the narrow-band terms compete with the broad-band. Once the narrow band effects are removed, the important broad-band contribution is seen cleanly.

Near the CW period, there is important broad-band forcing – the coherence typically increases, and is large, after the removal of the narrow-band orbital terms. An exception is shown in Figure 3, for northward velocity (v) at 63.8 S, where the primary effect is the orbital terms alone.

As the mechanism is general, small variations in earth-sun distance being translated to variations in the atmosphere (and thence ocean), we would expect there to be other fields which display signals at the orbital periods. Or, given how closely tied some of those orbital periods and CW are, other fields should show signals at the CW period itself. This has already been observed; sea ice [*Gloersen*, 1996] and sea surface temperature [*Kikuchi and Naito*, 1982] both show CW period variations. Lunar synodic period variations in MSU temperatures have already been mentioned [*Balling and Cerveny*, 1995]. It will be useful to examine other fields, and to re-examine these with methods and data which can distinguish between a broad-band CW feature and the narrow-band orbital terms. Since the time required by the Rayleigh criterion to separate a 433 day period from a 417 day period is at least 31 years, this is not a trivial requirement on the data.

This pacemaker also resolves the conflict between *O'Connor et al.* [2000] and [*Wunsch*, 2001] – the narrow band forcing from the atmospheric fields, thence ocean response, is due to the narrow band forcing by the earth's orbit. This mechanism supports conjectures regarding additional features of the earth's rotation. A long-standing discussion in the field is whether the Chandler Wobble is a single pure line, or multiplets. I suggest that it is multiple, based on the multiple lines which force the earth near the CW period, and that the balance between the forcing strength and the earth system response to it is what gives the observed CW. An additional feature of this is its accord with the long-standing observation of the time-varying spectrum of the CW, with multiple lines being suggested in, particularly, the earlier period of the record (before 1930) (e.g. *Lambeck* [1980]). As the ocean-atmosphere system evolves, it would be expected to move towards and away from stronger response to the small forcing from earth-sun distance. It is also observed that there are longer period variations in the earth's orientation and length of day, including decadal periods (e.g. *Lambeck* [1980]). Such periods also arise directly in the earth-sun distance spectrum, and as beats between some of the periods discussed here.

In the mean time, we see that meteorological fields are being forced by earth-sun distance variations, and that these variations are coherent with the observed variations in the earth's orientation.

Acknowledgments. I would like to thank W. P. O'Connor for his encouragement to pursue this idea. Data for earth-sun distance may be obtained from [*Giorgini et al.*, 1996]. Earth orientation and rotation from [*Gambis*, 2004]. NCEP/NCAR Reanalysis data were from http://nomad3.ncep.noaa.gov/pub/reanalysis-1/6hr/grb2d.

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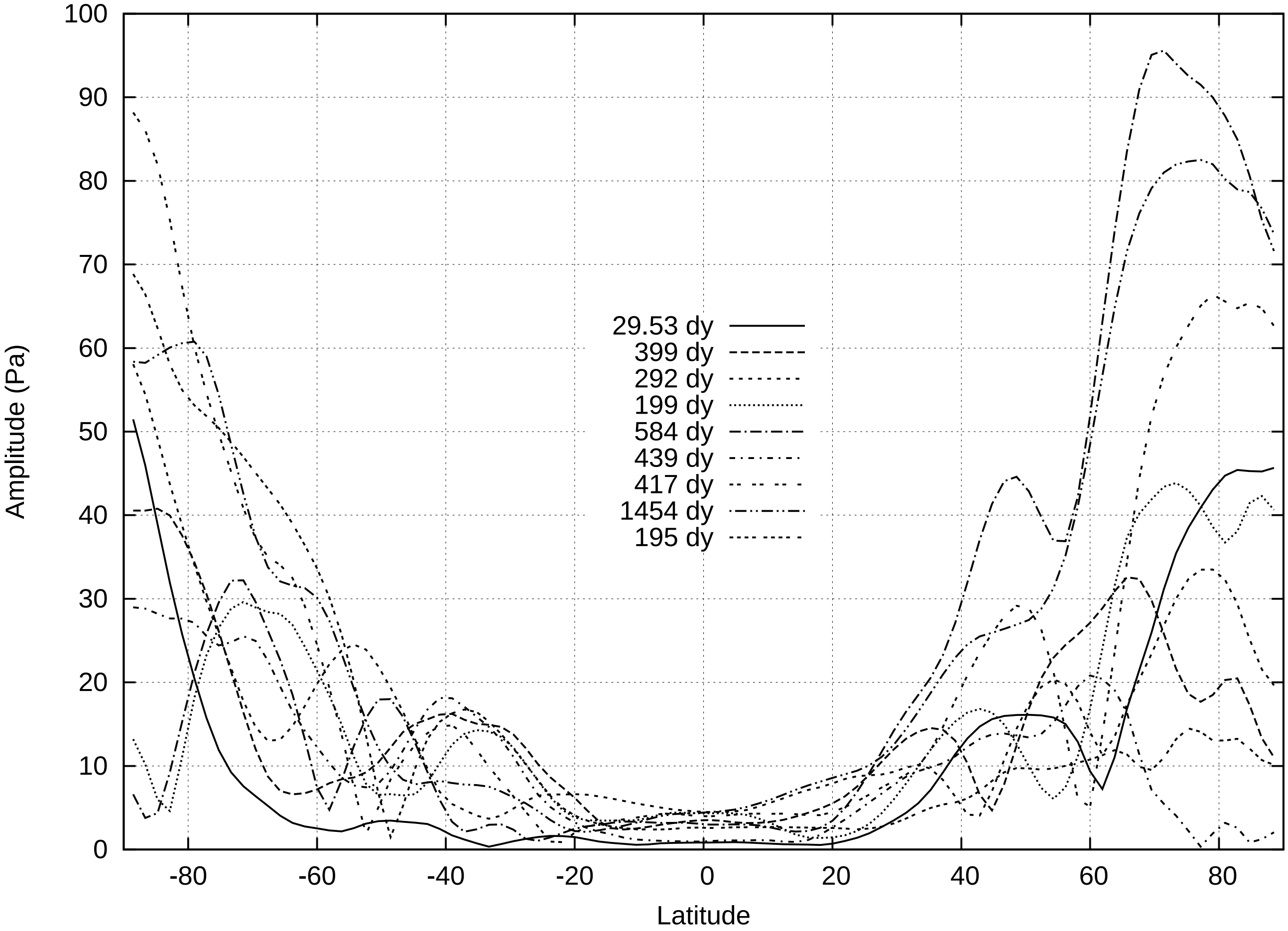

Figure 1. Amplitude of surface pressure (Pa) for principle orbital harmonics (29.53, 399, 292, 199, 584, 439, 417, 1454, and 195 days) versus latitude

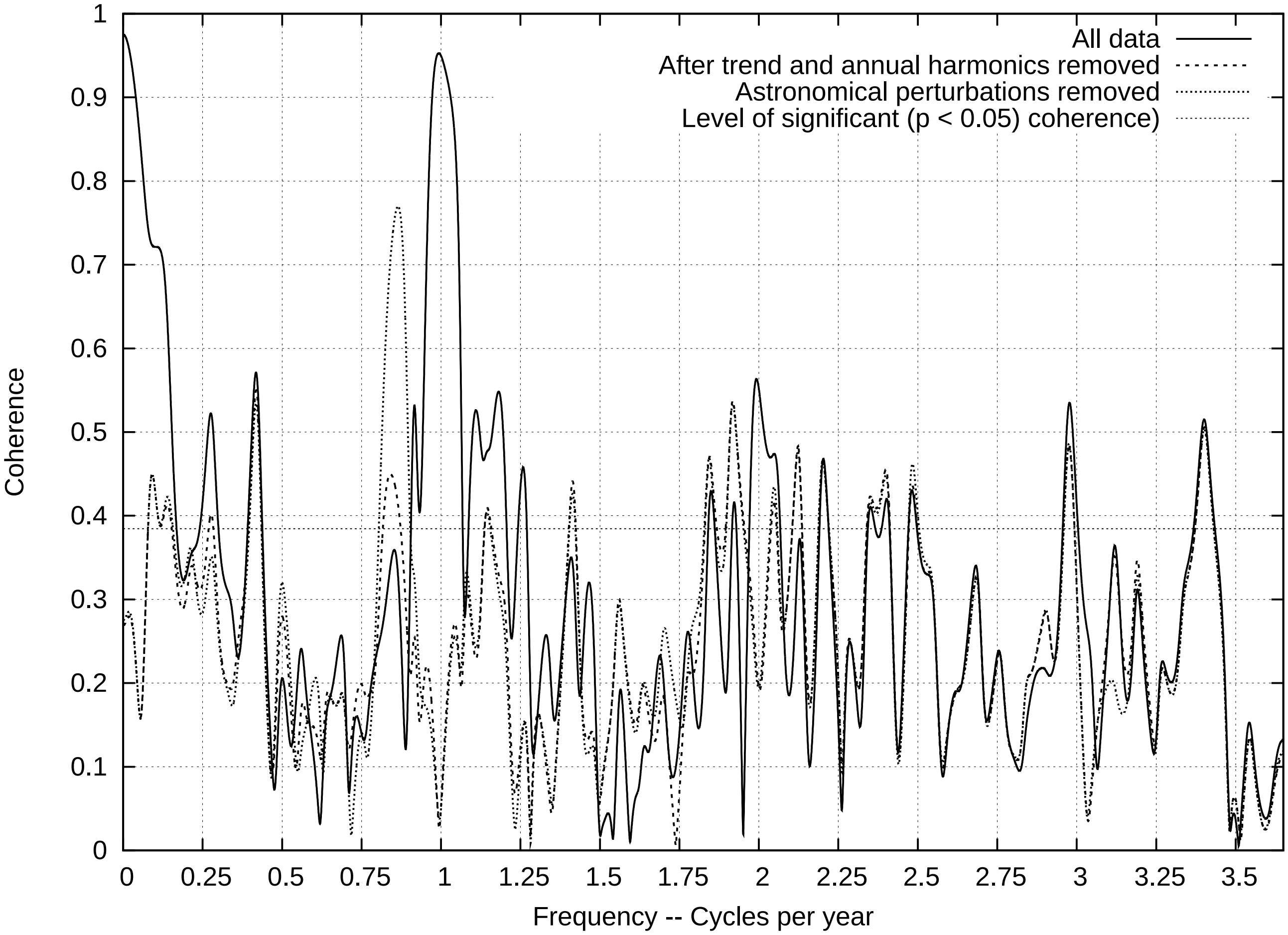

Figure 2. Coherence spectrum between v (northward wind speed) along 79 N and x displacement of earth's rotation axis.

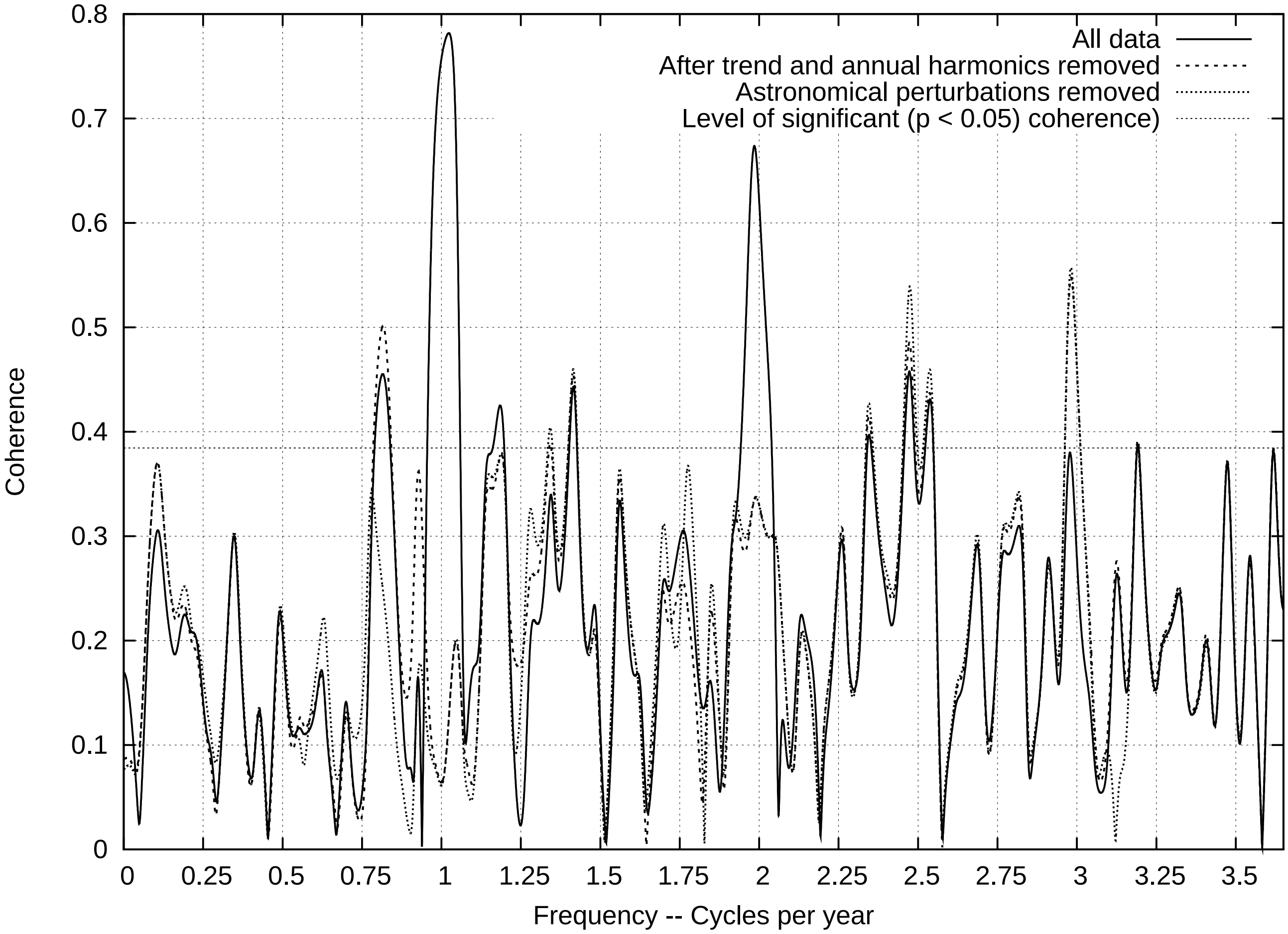

Figure 3. Coherence spectrum between v along 68.3 S and x displacement of earth's rotation axis.

Table 1. Summary of frequency (cycles per tropical year), amplitude, phase, period and origins of variations in earth-sun distance.[a]

Frequency (cpy)	Amplitude (10^{-6} AU)	Phase	Period (dy)	M	T	A	V	J
0.99995	16712.75	-177.9	365.260	0	0	1	0	0
1.99990	139.69	-175.8	182.630	0	0	2	0	0
2.99986	1.76	-173.9	121.753	0	0	3	0	0
12.36825	30.84	63.5	29.531	1	-1	0	0	0
0.91566	15.92	-143.5	398.884	0	1	0	0	-1
1.25100	15.63	31.0	291.961	0	-2	0	2	0
1.83132	9.27	-99.7	199.442	0	2	0	0	-2
0.62550	5.12	16.2	583.923	0	-1	0	1	0
0.87653	4.79	107.5	416.690	0	-4	0	3	0
0.83136	2.93	-137.3	439.332	0	1	0	0	-2
0.08430	2.58	70.2	4332.589	0	0	0	0	1
1.87649	2.54	-136.0	194.641	0	-3	0	3	0
1.75306	1.54	-98.5	208.345	0	-8	0	6	0
0.25103	1.53	-145.4	1454.951	0	-3	0	2	0
2.50199	0.91	61.5	145.981	0	-4	0	4	0
0.74706	0.64	146.4	488.908	0	1	0	0	-3
13.36821	0.57	-114.4	27.322	1	0	0	0	0
11.36829	0.56	61.3	32.128	1	-2	0	0	0
3.12749	0.37	-103.8	116.785	0	-5	0	5	0
0.50207	0.36	-71.8	727.476	0	-6	0	4	0
3.75299	0.20	94.1	97.320	0	-6	0	6	0
0.37446	0.14	156.7	975.374	0	2	0	-1	0

[a] Phase is in degrees, relative to 00 UTC 1 January 1962. The code lists the number of cycles per lunar sidereal month, per year (here I list both the tropical year and anomalistic year; the tropical year is used for motions involving the moon, Jupiter, and Venus), Venus's sidereal year, and Jupiter's sidereal year, respectively (M T A V J).