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Rotation of the Atmospheres of the Earth and Planets [and Discussion]

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Rotation of the atmospheres of the Earth and planets

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The most striking features of the general circulation of the Earth's atmosphere are its average 'super-rotation' relative to the solid Earth at about 10 m s^{-1}, and the concentration of much of the motion in jet streams with speeds of about 30 m s^{-1}. Changes in the pattern of winds, and variations in the distribution of mass within the atmosphere produce fluctuations in the angular momentum associated with this 'super-rotation', namely, the axial component H_3 of the total angular momentum of the atmosphere H_i, $i = 1, 2, 3$, and also in the equatorial components H_1 and H_2. Fluctuations in H_3 during the Special Observing Periods of the recent 'First GARP Global Experiment' (FGGE, where GARP is the Global Atmospheric Research Programme) later have been investigated. They are well correlated with short-term changes of up to about 10^{-3} s in magnitude in the length of the day (allowing for lunar and solar tidal effects on the moment of inertia of the solid Earth), exhibiting pronounced contributions on timescales of about seven weeks and one year and they are consistent with the sum of H_3 and the axial component of the angular momentum of the Earth's crust and mantle being conserved on short timescales, without requiring significant angular momentum transfer between the Earth's liquid core and overlying solid mantle on such timescales. Fluctuations in H_1 and H_2 on timescales much less than the Chandlerian period (14 months) but rather more than a few days make a major contribution to the observed wobble of the instantaneous pole of the Earth's rotation with respect to the Earth's crust, which has a variable amplitude of several metres. A theoretical basis has now been established for future routine determinations of fluctuations in H_i for the purposes of meteorological and geophysical research, including the assessment of the extent to which movements within the solid Earth associated with major earthquakes (magnitude much greater than 7.9) and motions in the liquid metallic core might occasionally contribute to the excitation of the Chandlerian wobble.

Venus's atmosphere 'super-rotates' at an average speed of about ten times that of the underlying planet, which, owing to angular momentum exchange with the atmosphere, should (like the solid Earth) undergo detectable changes in rotation period. Each of the giant planets Jupiter and Saturn exhibits a sharply-bounded equatorial atmospheric jet stream moving at 100 m s^{-1} (Jupiter) or 400 m s^{-1} (Saturn) in a positive (i.e. eastward) direction relative to higher latitude parts of the atmosphere, the average rotation of which is close to that of the hydrogen-metallic fluid interior (as determined from radio-astronomical observations). The theoretical interpretation of these observations presents challenging problems in the dynamics of rotating fluids.

1. INTRODUCTION

Seven years ago the Royal Society held a lively discussion meeting on methods and applications of ranging to artificial satellites and the Moon (see Cook & King-Hele 1977). I was asked to contribute a paper on fluctuations in the Earth's rotation, with particular reference to manifestations of the exchange of angular momentum between the solid and fluid parts of the

Earth. On that occasion, and also at an earlier meeting held in Sweden on the subject of future climate research (organized by the Joint Organizing Committee of the Global Atmospheric Research Programme (GARP) of the World Meteorological Organization and the International Council of Scientific Unions, see GARP (1975)), I was able to stress the need for atmospheric scientists, geodesists and other geophysicists to formulate joint projects in order fully to exploit the improved meteorological data then about to be acquired through the First GARP Global Experiment (FGGE) (see, for example, Bengtsson *et al.* 1982; Fleming *et al.* 1979; Oort 1983), and improved Earth's rotation data expected from the new monitoring techniques now being coordinated under the project MERIT (Monitoring Earth-Rotation and Intercompare the Techniques of observation and analysis). (MERIT was set up in 1978 by the International Astronomical Union and the International Union of Geodesy and Geophysics (see, for example, Carter *et al.* 1984; Christodoulidis & Smith 1983; Guinot 1979; Kahn & Cohen 1983; Mignard 1980; Robertson *et al.* 1983; Smith 1979; Smith & Kolenkiewicz 1979; Tapley 1983; Vicente 1979; Wilkins, this symposium; Wilkins & Feissel 1982).) But most busy scientists are understandably unresponsive to exhortations to join forces with others from different disciplines until they have been presented with convincing new results showing clearly where future collaborative research might lead. So I began to exploit my affiliation with a major meteorological centre to investigate, when time permitted, the extent to which short-term angular momentum fluctuations of the atmosphere can account for short-term changes in the length of the day and polar motion. Collaborators in this work, to whom it is a pleasure to express my gratitude, include several members or former members of this laboratory, namely Mr R. T. H. Barnes, Mr R. D. Carter, Dr A. A. White and Dr C. A. Wilson. With the help of various institutions, including the National Center for Atmospheric Research and National Meteorological Center in the U.S.A., the Royal Greenwich Observatory and the European Centre for Medium Range Weather Forecasts in the U.K., and the Bureau International de l'Heure in France, we were able to obtain several interesting new results which had important meteorological and geophysical implications (see §2 and Appendix), and which led eventually in 1983 to the setting up by the International Association for Geodesy of a Special Study Group (chaired by Dr Jean Dickey of the Jet Propulsion Laboratory) charged with the task of improving and promoting further collaborative work in this general area.

The study of the rotation of the atmospheres of some of the other planets (and of the Sun) is now well established, having developed gradually over the past few decades. But observations are much less detailed than for the Earth and the scientific questions correspondingly rudimentary (see, for example, Gehrels 1976, 1983; Hide 1965, 1966, 1981; Howard 1978; Hunt 1983; Ingersoll *et al.* 1979, 1981; Schubert 1983). One of the most striking features of the general circulation of the Earth's atmosphere is its slow average 'super-rotation' (a term originally coined to describe the motion of the tenuous thermosphere: see, for example, Winterbottom & King-Hele 1984) relative to the solid Earth. The atmosphere of the planet Venus also super-rotates, at an average speed of about *ten times* that of the underlying solid surface which, owing to angular momentum exchange with the atmosphere, should (like the solid Earth) undergo detectable changes in rotation period. The giant planets Jupiter and Saturn, unlike the terrestrial planets, are thought to be fluid throughout. They exhibit sharply-bounded equatorial atmospheric jet-streams moving at about 100 m s^{-1} (Jupiter) or 400 m s^{-1} (Saturn) relative to the higher latitude parts of the atmosphere, the rotation of which is close to that of the hydrogen-metallic interior (as determined from radio-astronomical observations, see for example, Gehrels 1976, 1983). The interpretation of these and related observations of planetary atmospheres presents challenging problems in the dynamics of rotating fluids which are now attracting much attention from theoreticians (see §3).

2. SHORT-TERM VARIATIONS IN THE LENGTH OF THE DAY AND POLAR MOTION

In the absence of internal energy sources or mechanical, gravitational, or radiative interactions with other astronomical bodies, the whole Earth would move as a rigid body, with its solid parts (crust, mantle, and inner core) and fluid parts (atmosphere, hydrosphere, and outer core) all rotating together at a constant rate about a fixed axis of maximum moment of inertia through the Earth's centre of mass. Positional astronomers equipped with perfect telescopes and clocks would find no variation in the astronomical latitude of any observatory, nor in the angular rate at which all fixed stars appeared to circle the Celestial Pole. The successful use of the rotation of observatories fixed on the Earth's crust as the basis of early attempts to provide a practical scale of time attests to the validity of this picture as a good first approximation to the truth (see, for example, Gaposchkin & Kolaczek 1981). However, over the years, as clocks based on other periodic physical phenomena were exploited and the methods of positional astronomy were improved, there came to light tiny fluctuations in the length of the day, as measured by the time interval between successive transits of a particular star across the meridian, and slight movements of the Earth's pole of rotation (usually called polar motion or 'wobble'), manifested at a given station by variations in its astronomical latitude. Typically the length-of-day shows variations of up to a few milliseconds on timescales from days to years, while the rotation pole executes rough ovals, a few metres in size and somewhat longer than a year in period, in the vicinity of the geographical reference pole (the Conventional International Origin).

Interpreting variations in the magnitude and direction of the Earth's rotation vector in terms of energetic processes and angular momentum transfer within the Earth–Moon system is a fascinating scientific problem, which brings together many diverse areas of study, notably solid Earth geophysics, geodesy, meteorology, oceanography, hydrology, glaciology, geomagnetism, palaeoclimatology, astrometry, and even aspects of historical scholarship. Such studies of the Earth's rotation go back to the last century. The first thorough review of the subject was presented by Munk & MacDonald (1960), and Lambeck (1980) has given an up-to-date discussion taking into account recent advances in geodynamics, instrumentation and international cooperation.

Unless otherwise stated, we shall use the term 'Earth' to mean the core, mantle, crust and hydrosphere, that is, the whole Earth minus the atmosphere, and the term 'solid Earth' to mean the crust and mantle. Variations in the rotation of the solid Earth can be caused by (i) changes in the total angular momentum or moment of inertia due to the application of external forces (lunar and solar gravitational attraction on the equatorial bulge, bodily tides, the solar wind), (ii) changes in the inertia tensor due to internal effects (e.g. earthquakes), and (iii) exchange of angular momentum with the overlying oceans and atmosphere and underlying fluid core. External effects (i) are now largely calculable and so may adequately be subtracted from astronomical observations, leaving the determination of the relative importance of effects (ii) and (iii) as a geophysical problem.

During the past few years, the Geophysical Fluid Dynamics Laboratory of the U.K.

Meteorological Office has undertaken a systematic investigation of the extent to which short-term changes in the magnitude and direction of the rotation vector of the solid Earth can be accounted for in terms of angular-momentum exchange with the atmosphere (Hide 1977; Hide *et al.* 1980; Barnes *et al.* 1983, cited as BHWW), and the present summary of the main findings of that work is based on the introductory section to BHWW.

Denote by H_i, $i = 1, 2, 3$, the total angular momentum of the atmosphere about the Earth's centre of mass. The magnitude of H_i is about 10^{-6} that of the whole Earth. All three of its components exhibit variations on timescales upwards of a few days, and reflect changes in the distribution of mass in the atmosphere and in the pattern of winds, particularly the strength and location of the major mid-latitude jet-streams. Fluctuations in H_i are of interest to meteorologists concerned with the general circulation of the atmosphere, since they are gross indicators of changes in the strength of the zonal circulation and in the surface pressure distribution. The consideration of these fluctuations can provide useful constraints on numerical models of the general circulation, since the time rate of change of angular momentum $\dot{H}_i$ must equal the torque exerted at the surface, and this requires the satisfactory representation both of motions in surface boundary layers and of topographic effects on air flow. Atmospheric angular momentum fluctuations are of interest also to geophysicists and astronomers concerned with the structure and dynamics of the Earth, who must make allowances for the meteorological contribution to the variable rotation of the solid Earth when dealing with effects due to 'non-meteorological' processes (see, for example, Brosche & Sündermann 1982; Etkins & Epstein 1982; Hide 1977; Lambeck 1980; Mansinha *et al.* 1970; Rochester, this symposium; Runcorn *et al.* 1982; Wu & Peltier 1984; Yoder *et al.* 1981).

Comparison of astronomical observations of changes in the rotation of the solid Earth with variations of H_i as determined from meteorological data elucidates the significance of atmospheric contributions to changes in length-of-day and to the excitation of polar motion. Several studies (see, for example, Lambeck & Cazenave 1977; Lambeck & Hopgood 1982; Rudloff 1973) have related length-of-day variations to changes in H_3 on timescales ranging from months to a few years. The atmospheric contribution to the forced motion of the pole has been investigated by several workers (Munk & Hassan 1961; Sidorenkov 1973; Wilson & Haubrich 1976), who concentrated on the effects of the re-distribution of mass on the atmosphere's inertia tensor, and thus found evidence of meteorological excitation of the annual component of polar motion. All these studies used mean monthly or longer period atmospheric data.

There are also rapid and irregular variations in length-of-day and polar motion on timescales of days and weeks. Hide *et al.* (1980) compared length-of-day data from the Bureau International de l'Heure (B.I.H.) with determinations of daily values of the axial component of H_i from wind data collected during the Special Observing Periods of the FGGE: see Fleming *et al.* (1979). The correlations found on these short timescales could (within the small errors involved) be fully accounted for on the basis of angular momentum exchange between the atmosphere and solid Earth, which implies that angular momentum transfer between the Earth's liquid core and solid mantle, which is considered to be substantial and even dominant on timescales upwards of a few years (see, for example, Munk & MacDonald 1960; Hide 1977; Lambeck 1980; Runcorn *et al.* 1982), is probably not significant on much shorter timescales. After removing known tidal effects from B.I.H. length-of-day values for 1979, Feissel & Gambis (1980) (see also Feissel & Nitschelm (1984)) noticed a persistent fluctuation on a timescale of about 7 weeks, with an amplitude of up to about 0.4 ms. The work of Hide *et al.* (1980) implied that H_3 should exhibit a similar fluctuation, and this expectation was confirmed by Langley *et al.* (1981) and Rosen & Salstein (1983) (see also Carter *et al.* 1984) from their studies of several years of axial atmospheric angular momentum values, as evaluated from the daily global wind data of the U.S. National Meteorological Center. The successful elucidation of this 7-week fluctuation in the atmospheric angular momentum will in my opinion constitute a major future advance in our understanding and ability to predict the behaviour of large-scale features of the general circulation of the atmosphere.

BHWW made the first quantitative attempt to relate short term variations in H_1 and H_2, the equatorial components of H_i, to irregularities in polar motion. While changes in the distribution and strength of zonal winds provide the main contribution to fluctuations in H_3 and hence to changes in length-of-day, it is the redistribution of air mass that is largely responsible for altering H_1 and H_2 and thus exciting a wobble in the orientation of the Earth with respect to its rotation axis. BHWW calculated daily values of H_1 and H_2 for the period 1 January 1981–30 April 1982, using the surface pressure and eastward and northward wind fields of the 'initialised analysis global database' archived by the European Centre for Medium-Range Weather Forecasts (E.C.M.W.F.). The results were used in a comparison with the values of length-of-day and polar motion published by the B.I.H. Identical atmospheric quantities are now being evaluated by other groups from the wind and surface pressure fields of the U.S. National Meteorological Center's (N.M.C.) global database, and it is hoped that comparison of the two sets of atmospheric angular momentum values will furnish further information on the accuracy and reliability of our results. (This approach to the problem of error estimation proved to be the most practicable in the work of Hide *et al.* (1980) on the axial component.) Some recent findings are presented in figures 1–4.

BHWW found it necessary to re-examine the theory of wobble excitation (see Munk & MacDonald 1960; Lambeck 1980; Wahr 1982, 1983) by considering carefully the dynamical coupling between the atmosphere and the underlying solid Earth. The excitation functions $(\psi_1, \psi_2) \equiv \boldsymbol{\psi}$ used by the previous workers are proportional to the equatorial components of the total frictional and pressure torque on the solid Earth. Thus $\boldsymbol{\psi}$ cannot be evaluated reliably from meteorological data by applying inviscid forms of the equations of atmospheric motion or by neglecting topography. Instead of attempting to evaluate $\boldsymbol{\psi}$ directly, values of a new atmospheric equatorial effective angular momentum (e.a.m.) function $\boldsymbol{\chi}$ were calculated (see Appendix). This function includes Love number corrections for rotational and surface loading deformation of the Earth and can (unlike $\boldsymbol{\psi}$) be evaluated reliably from available meteorological data. Full allowance for the response of the oceans to atmospheric surface pressure changes was not made in the main part of the study, but it was shown that the use of an 'inverted barometer' correction may not substantially change the results.

The results (see figures 1 and 2) confirm the previous finding of Hide *et al.* 1980 that short-term changes in the length of the day could be accounted for on the basis of transfer of axial angular momentum between the atmosphere and solid Earth (i.e. crust and mantle). This transfer exhibits persistent fluctuations on a timescale of about seven weeks with an amplitude of about 15% of the total relative angular momentum of the atmosphere, the corresponding changes in length-of-day being near 0.5×10^{-3} s (see BHWW; also Anderson & Rosen 1983; Eubanks *et al.* 1983; Feissel & Gambis 1980; Hide *et al.* 1980; Langley *et al.* 1981; Rosen & Salstein 1983). Respective contributions to this seven-week fluctuation from the northern and southern

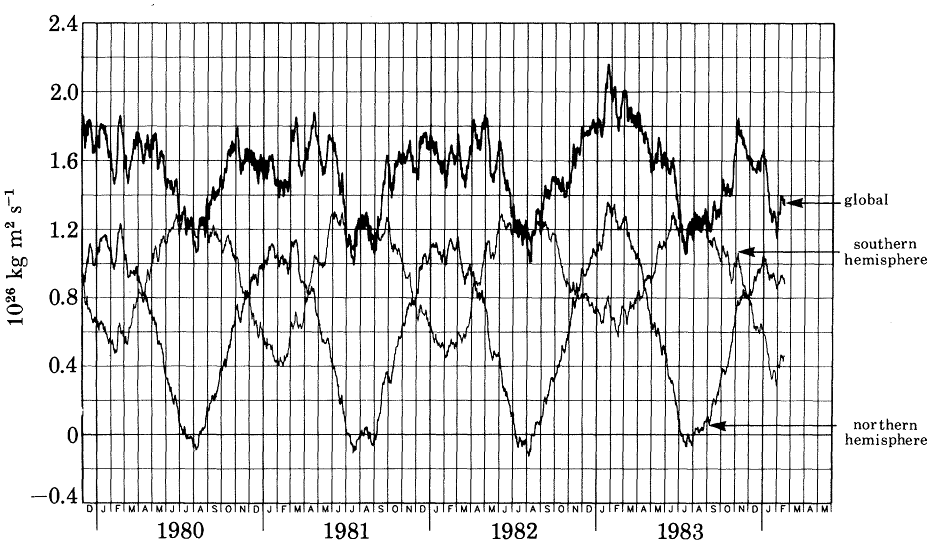

FIGURE 1. Daily values of the axial component of the total relative angular momentum of the Earth's atmosphere during the interval 1 December 1979–15 February 1984, together with contributions from the northern and southern hemispheres.

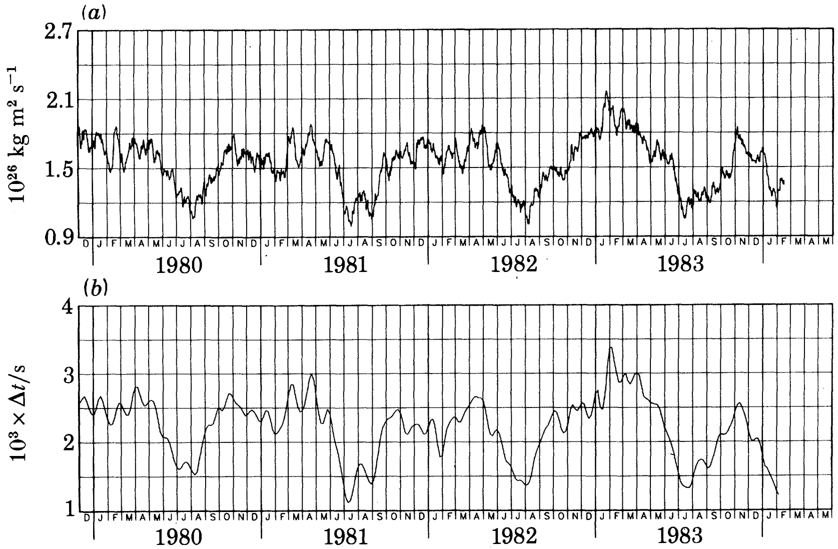

FIGURE 2. Angular momentum fluctuations of the atmosphere (*a*) and changes in the length of the day (*b*) from 1 December 1979 to 15 February 1984. There is good agreement between time-variations of the corresponding axial atmospheric effective angular momentum function χ_3 defined by (A 3) and the quantity $\chi_3[m_3] \equiv \Delta\Lambda/\Lambda_0 - \langle \Delta\Lambda/\Lambda_0 \rangle$ (see (A 7), cf. BHWW, figure 5), implying that short-term changes in the length of the day can be accounted for virtually entirely in terms of axial angular momentum exchange between the atmosphere and solid Earth, without having to invoke significant non-meteorological excitation on these short timescales. These results effectively confirm and extend the work of Hide *et al.* (1980) (see also BHWW), which was based on the most comprehensive meteorological data sets ever obtained, albeit for the limited duration of the two Special Observing Periods (4 January–5 March and 1 May–30 June) in 1979 of the FGGE. By continuing these calculations on a routine basis with the best meteorological and length-of-day data available it will be possible to investigate in detail the non-meteorological processes that influence the rate of rotation of the solid Earth on longer timescales. (The length of the day is $86400 + \Delta t$ s.)

hemispheres are comparable in magnitude and show little systematic difference in phase. These findings strongly imply that the fluctuation is of intrinsic origin, and driven by dynamical atmospheric processes occurring in the Tropics.

Since 1975 the amplitude of the polar motion (wobble) diminished gradually from about 9 m to a minimum of about 3 m towards the end of 1980, and then began to increase slowly (see Guinot 1982; Hinderer *et al.* 1982; Mulholland & Carter 1982; Okamoto & Kikuchi 1982; Okubo 1982*a*, *b*). Our evaluation of the atmospheric equatorial effective angular momentum functions from meteorological data over an interval corresponding to 3.6 Chandlerian periods indicates that atmospheric excitation alone was sufficient to account for the observed polar motion over that interval (see figures 3 and 4). There is apparently no need to invoke substantial excitation either by the fluid core of the Earth, or movements in the mantle associated with earthquakes, of which, admittedly, there were no major instances during the interval covered by our study. There were several earthquakes exceeding 7.2 in magnitude during the interval covered by our study, but none exceeded 7.9. If the new I.A.G. Special Study Group on atmospheric excitation of the Earth's rotation is successful in its efforts to establish a programme for applying the results BHWW to the routine monitoring of the atmospheric contribution to changes in the angular momentum of the solid Earth, then it will be possible to determine by subtraction any non-atmospheric contributions that might be present from time to time, and in particular to assess whether or not processes associated with major earthquakes are important in this connection. It will also be possible in this way to obtain further evidence bearing on the preliminary finding of Hide *et al.* (1980) and BHWW that angular momentum transfer

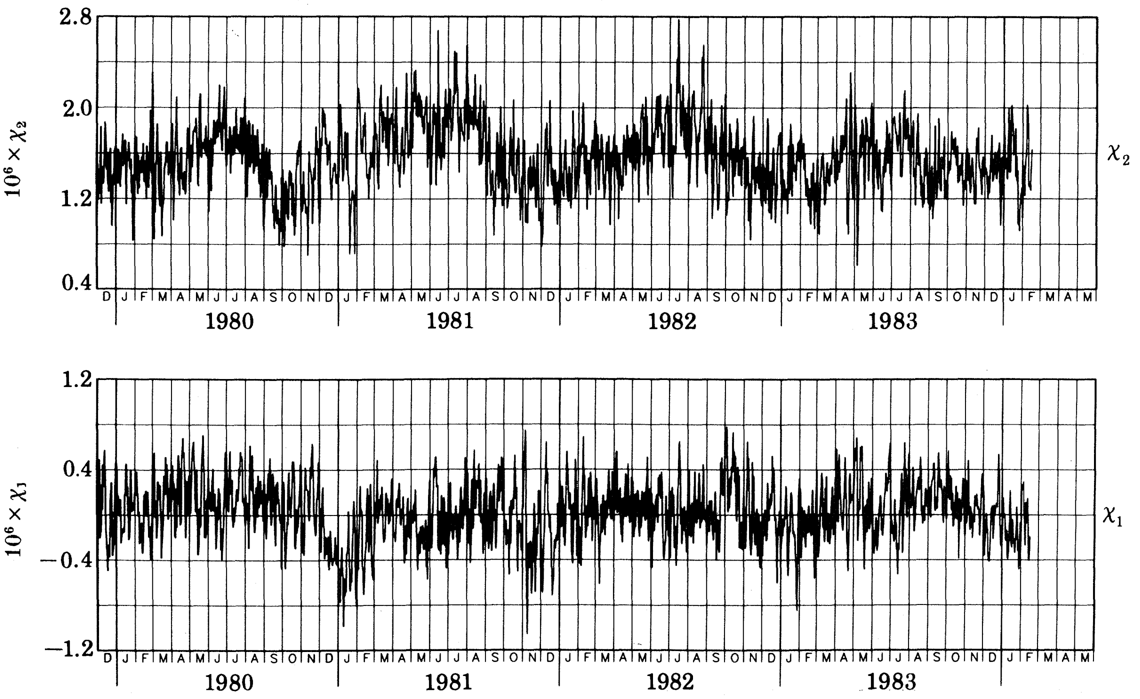

FIGURE 3. Daily values of the atmospheric equatorial effective angular momentum functions χ_1 and χ_2 (see equations (A 1) and (A 2)) during the interval 1 December 1979–15 February 1984.

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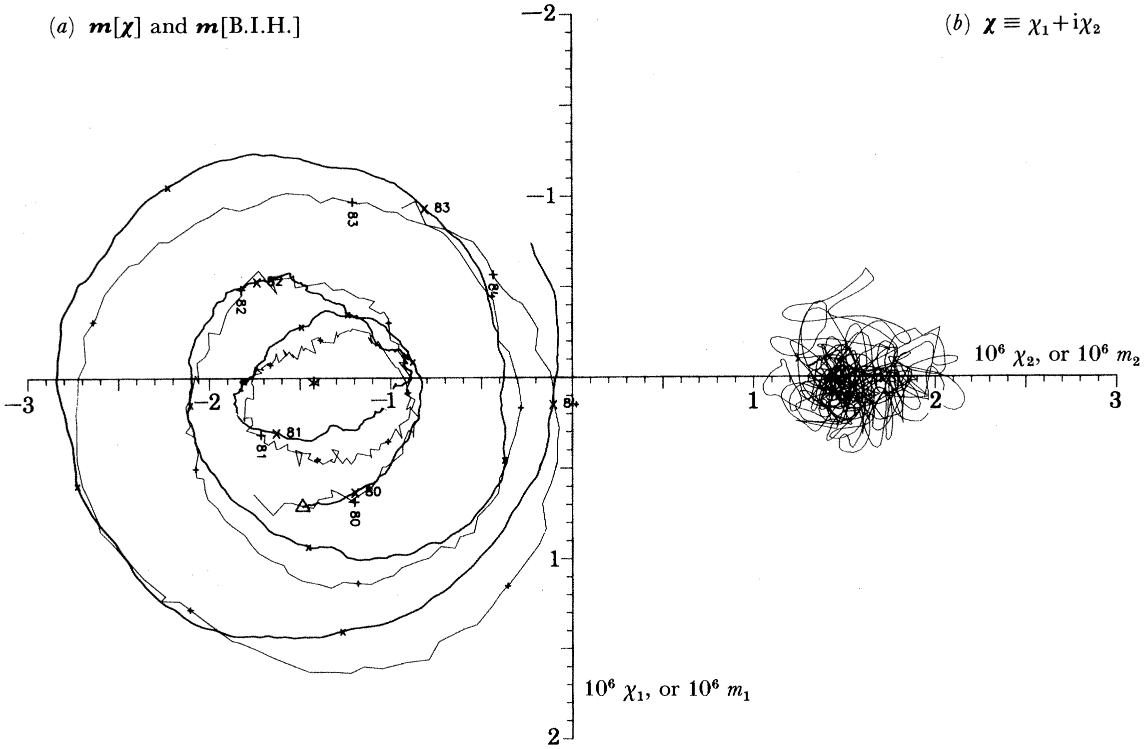

Figure 4. Demonstration that the observed polar motion during the interval 1 December 1979–15 February 1984, can be accounted for in terms of angular momentum exchange between the atmosphere and solid Earth, without having to invoke significant non-meteorological excitation. Figure 4*a* compares the observed polar motion $\boldsymbol{m}$[B.I.H.] (—+—), as determined by the Bureau International de l'Heure, with the expected polar motion $\boldsymbol{m}[\boldsymbol{\chi}]$ (—×—) calculated on the basis of (A 9) with the time-series of χ_1 and χ_2 given in figure 3 as input. $\boldsymbol{m} \equiv m_1 + \mathrm{i}m_2$ and $\boldsymbol{\chi} \equiv \chi_1 + \mathrm{i}\chi_2$ (see equations (A 1), (A 2) and (A 5)). The units of both axes are radians: 10^{-6} rad is equivalent to a displacement of about 6.4 m over the Earth's surface. Figure 4*b* is a polar plot of smoothed (for convenience of display) values of $\boldsymbol{\chi}$ based on figure 3. These results effectively confirm the findings of BHWW), by extending the duration of the comparison of the observed and meteorologically excited polar motion from 1.1 to 3.6 Chandlerian periods and showing that good agreement evidently still persists. By continuing these calculations on a routine basis with the best meteorological and polar motion data available it will be possible to investigate the damping of polar motion and non-meteorological excitation processes. (Note that the curve $\boldsymbol{m}[\boldsymbol{\chi}]$ is based on daily values of $\boldsymbol{\chi}(t)$ for the interval t_0 (1 December 1979) to t_1 (15 February 1984), over which the mean value of $\boldsymbol{\chi}$ was 10^{-6} $(0.025 + 1.56\mathrm{i})$. The initial conditions at $t = t_0$ (see equation (A 9)) were as follows: $\boldsymbol{m}[\boldsymbol{\chi}] = \boldsymbol{m}$[B.I.H.] $= 10^{-6}$ $(0.71 - 1.49\mathrm{i})$ (see point indicated by △); $\boldsymbol{\chi}'(t_0) \equiv \boldsymbol{\chi}(t_0) + \langle\boldsymbol{\chi}\rangle = 10^{-6}$ $(0.025 - 1.425\mathrm{i})$ (see point indicated by *). $\boldsymbol{\chi}'(t_0)$ was judged by eye as the instantaneous centre of curvature of the $\boldsymbol{m}$[B.I.H.] curve at $t = t_0$. Time marks (× meteorological; + astronomical) are given at intervals of three months, with those corresponding to 1 January 1980, 81, 82, 83 and 84 labelled 80, 81, 82, 83, 84 respectively.)

between core and mantle does not seem to occur to any significant extent on timescales much less than a few years.

No mention has yet been made of the cause of atmospheric super-rotation and of the fluctuations in the angular momentum of the atmosphere H_i. The discussion of the fluid-dynamical processes involved will lie at the heart of a satisfactory theory of the general circulation of the atmosphere, and in particular of the coupling between the atmosphere and the underlying surface. All components of $\dot{H}_i$ would be zero if that surface were perfectly spherical and perfectly slippery, for then normal stresses would exert no couple and tangential (frictional) stresses would be absent. In practice both 'topographic' and frictional stresses are present, with normal pressure forces acting on the Earth's equatorial bulge playing a major role in the coupling associated with the changes in H_i that manifest themselves in the observed polar motion (see BHWW). A full discussion of these dynamical questions lies beyond the scope of the present article, but it is worth noting that numerical models of the atmosphere are now approaching a level of sophistication at which meaningful detailed experiments on angular momentum exchange between the atmosphere and solid Earth could be done.

3. ROTATION OF THE ATMOSPHERES OF THE OTHER PLANETS

The study of differential rotation of planetary atmospheres and other geophysical and astrophysical fluid systems has been the subject of many theoretical investigations, and numerous relevant references are given in articles by Belvedere *et al.* 1980; Busse & Hood 1982; Gilman & Foukal 1979; Glatzmeier & Gilman 1981; Hasegawa 1983; Hide & James 1983; Kundt 1983; Mayr *et al.* 1981; Rüdiger 1982; Schmidt 1982; Schubert 1983; Tassoul 1978; Thompson 1980; Williams 1979; where discussions of a wide variety of simplified models can be found. These models give considerable insight into a number of important dynamical processes and provide a rough basis for the interpretation of observations. But certain observational errors will have to be reduced and models improved before truly detailed studies can be made. We conclude this brief review with some remarks about the rotation of some of the planets, but without attempting a systematic or comprehensive treatment.

Thanks to the findings of recent space missions to the planet Venus and of certain ground based observations, there now exists an extensive literature on various aspects of the dynamics and the closely-linked thermal structure of the dense Venusian lower atmosphere (see, for example, Allen & Crawford 1984; Covey & Schubert 1981; Ingersoll & Dobrovolskis 1978; Ingersoll *et al.* 1979; Kerzhanovich & Marov 1983; Schofield & Diner 1983; Schubert 1983; Seiff 1983; Taylor *et al.* 1983). The most striking feature of the motion of Venus's atmosphere is its very rapid super-rotation relative to the underlying planet which, according to radar observations, rotates (in a retrograde sense) in a period of 243 days. This is about ten times the average period of rotation of the atmosphere and over fifty times the period of rotation of features at the upper cloud level, which was first determined from ground-based observations of reflected solar ultraviolet light from the planet. The relative angular momentum associated with the super-rotation is so great that quite modest fluctuations in its value would be associated with changes in the rotation rate of the underlying planet that might be detectable by radar methods (cf. §2 above).

Whether or not internal dynamical processes of the kind discussed in the above-mentioned references to theoretical studies of differential rotation in geophysical and astrophysical fluid systems can account for the enormous value of Venus's atmospheric super-rotation is not yet clear. Asserting that such processes may be inadequate, Gold & Soter (1971) invoked the action of external couples due to the gravitational action of the Sun on non-axisymmetric atmospheric density variations associated with thermal tides (see also Dobrovolskis 1980; Dobrovolskis & Ingersoll 1980; Ingersoll & Dobrovolskis 1978; Schubert 1983). External couples might suffice if the vertical temperature gradient in Venus's atmosphere is sufficiently sub-adiabatic to suppress small-scale turbulence, but not otherwise.

While the atmosphere of Venus is dense, with a surface pressure about 100 times that of the Earth's atmosphere, the atmosphere of Mars is very tenuous, with a surface pressure less than

10^{-2} times the terrestrial value. Horizontally-extensive topographic features on the Martian surface are typically comparable in their vertical dimensions with the scale height of the atmosphere, so it is hard to make any useful statement about the average rotation of the atmosphere relative to the underlying planet, although there is much interest in other aspects of the dynamics of the Martian atmosphere (see, for example, Leovy 1979). Philip (1979) and Cazenave & Balmino (1981) have discussed angular momentum variations of seasonally-condensing atmospheres with special reference to Mars.

Jupiter, the largest and most massive of the nine planets, is generally considered to be fluid throughout (the main constituent being hydrogen, with helium as the principal 'impurity'), so there are no natural fixed features with respect to which longitude can be measured. The observations that led to Cassini's discovery of Jupiter's rotation were made by Campani in 1665 and reported in the first paper published in the Philosophical Transactions of the Royal Society, at about the same time that Hooke reported a marking that might have been the Great Red Spot, but systematic measurements of the motion of atmospheric markings at different latitudes were not done until much later. These revealed a latitudinal variation of atmospheric rotation rate and led to the introduction of system I, rotation period 9 h 50 min 30.003 s, for convenience when studying markings within about ±7° of the equator, and system II, rotation period 9 h 55 min 40.632 s (equal to the average rotation period of the Great Red Spot during the 1890–91 apparition), for higher-latitude features. Following their discovery in 1956 of non-thermal radio-emission from Jupiter, radio-astronomers found neither system I nor system II convenient for monitoring the emission and therefore introduced system III with a rotation period 9 h 55 min 29.370 s, which they later changed to its present value of 9 h 55 min 29.710 s (Gehrels 1976; May *et al.* 1979). The use of system III is now gaining favour with all Jovian observers. (For references see Gehrels 1976; Hide 1981.)

It is convenient to divide the interior of Jupiter into two regions, a 'core' of mean radius r_c within which the electrical-conductivity σ is so high that fluid motions there are capable of generating the Jovian magnetic field $\boldsymbol{B}$ by the self-exciting hydromagnetic dynamo process. The core is surrounded by a non-conducting layer extending to the ammonia-cirrus atmospheric upper cloud deck at the visible surface of mean radius $r_s = 69\,700$ km. The interpretation of Jupiter's non-uniform rotation involves considerations of the hydrodynamics of the outer layer and the hydromagnetics (magnetohydrodynamics) of the core (Hide 1965), just as the interpretation of the general westward motion of the geomagnetic field at about 3×10^{-4} m s^{-1} (relative to the solid Earth) and the general eastward motion (on average) of the terrestrial atmosphere at about 10 m s^{-1} and differential atmospheric rotation involves considerations of the fluid motions in the Earth's liquid core and atmosphere respectively, and their coupling with the mantle.

The variation of large-scale zonal flow with latitude as evinced by the motions of extensive markings on Jupiter's visible disc has been studied by several workers (for references see Gehrels 1976; Beebe *et al.* 1980; Ingersoll *et al.* 1981; Hunt 1983), with recent discussions making use of the magnificent high-resolution pictures obtained from the Voyager 1 and Voyager 2 Jupiter fly-bys in 1979. The most striking feature revealed by these observations is a sharply-bounded equatorial jet of width $2r_s\,\Delta\theta = 20\,000$ km where $\Delta\theta \approx 7° \approx 10^{-1}$ rad moving in a westerly sense relative to system III (and system II) with a speed $U \simeq 100$ m s^{-1}. This jet has counterparts in the terrestrial oceans (Cromwell Current) and atmosphere and in the atmosphere of Saturn, for which observations show that U exceeds 400 m s^{-1} and $\Delta\theta \approx 20°$ (see below).

The westerly sense of the Jovian jet shows that it must be produced by non-axisymmetric dynamical processes. These complicate the theory, but quite straightforward general dynamical arguments based on considerations of vorticity balance suffice to show that

$$\Delta\theta \approx (U/r_s\,\Omega)^{\frac{1}{2}}, \tag{3.1}$$

where Ω is the mean angular speed of rotation of the planet (Hide 1966). This expression is in fair agreement with the observations of equatorial jets on Jupiter and Saturn.

Jovian non-thermal radio sources are extensive regions of plasma tied to the lines of force of the magnetic field $\boldsymbol{B}$ surrounding the planet, and the motion of these sources (upon which system III is based) gives the rotation of the pattern of Jupiter's magnetic field. Now, $\boldsymbol{B}$ itself is produced in Jupiter's electrically-conducting fluid core (see Hide 1965; Gehrels 1976), mean radius r_c, by self-exciting hydromagnetic dynamo action there, and it can be supposed that any relative motion between the upper reaches of the core and the lines of force of $\boldsymbol{B}$ is negligibly small, no more than about 10^{-2} m s^{-1}, so that any absolute difference between the motion of the core and that of system III amounts to less than 1 part in 10^6. In the study of the rotation of Jupiter it is clearly a matter of importance to determine r_c as accurately as possible.

Hide (1978) has introduced a method for finding r_c which exploits the fact that over short time intervals the number of lines of magnetic force intersecting the surface of the core cannot change significantly. This method makes use of secular changes in the magnetic field in the accessible region above the surface of the planet. When applied to the Earth with the best available determinations of the geomagnetic secular variation the method gives r_c to within 2% of the more accurate 'seismological' value, but even the best Jovian magnetic field observations available for this purpose are not yet good enough to give a reliable value of r_c for Jupiter. The rough determinations that have been made could be greatly improved on in the future if detailed magnetic observations can be done with the aid of the Jupiter orbiter on the forthcoming 'Galileo' mission, which will be launched by the 'Shuttle/Centaur' in the late spring of 1986 with the objective of making, starting in August 1988, a far more comprehensive study of the Jovian system than was possible with the highly successful 'Voyager' and 'Pioneer' missions.

The planet Saturn is second only to Jupiter in size and mass and, like Jupiter, is generally considered to be fluid throughout. Ground-based observations of transits of long-lived spots yield atmospheric rotation periods of 10 h 13 min within about 20° of the equator and 10 h 40 min at higher latitudes. 'Voyager' observations provided important new details, confirming the presence at the upper cloud level of Saturn's atmosphere of an equatorial current moving eastward at more than 400 m s^{-1}, four times the speed of Jupiter's equatorial current. As noted above, (3.1) indicates that the width of Saturn's equatorial current should be more than twice that of Jupiter's, and this is in accordance with the observations.

Studies of Saturn's non-thermal radio emission give a rotation period of about 10 h 40 min for material deep within the planet, at the level $r = r_c$. The value of r_c is not yet accurately known, but it is expected to be proportionately significantly less than for Jupiter.

Appendix. Atmospheric excitation of short-term changes in the length of the day and polar motion

The dimensionless atmospheric 'effective angular momentum' (e.a.m.) functions mentioned in §2 above, which facilitate the analysis of the dynamical interaction of the atmosphere with the solid Earth, comprise the equatorial components χ_1 and χ_2 and the axial component χ_3 of the pseudo-vector χ_i, $i = 1, 2, 3$, (see BHWW, especially §5), where (χ_1, χ_2, χ_3) are defined as follows:

$$\chi_1 \equiv \frac{-1.00\,\bar{R}^4}{(C-A)\,g} \oint\!\!\oint p_s \sin\phi \cos^2\phi \cos\lambda \,\mathrm{d}\lambda\,\mathrm{d}\phi \\ \frac{-1.43\,\bar{R}^3}{\Omega(C-A)\,g} \oint\!\!\oint\!\!\oint (u \sin\phi\cos\phi\cos\lambda - v\cos\phi\sin\lambda)\,\mathrm{d}\lambda\,\mathrm{d}\phi\,\mathrm{d}p, \qquad (\mathrm{A}\ 1)$$

$$\chi_2 \equiv \frac{-1.00\,\bar{R}^4}{(C-A)\,g} \oint\!\!\oint p_s \sin\phi \cos^2\phi \sin\lambda \,\mathrm{d}\lambda\,\mathrm{d}\phi \\ \frac{-1.43\,\bar{R}^3}{\Omega(C-A)\,g} \oint\!\!\oint\!\!\oint (u \sin\phi\cos\phi\sin\lambda + v\cos\phi\cos\lambda)\,\mathrm{d}\lambda\,\mathrm{d}\phi\,\mathrm{d}p, \qquad (\mathrm{A}\ 2)$$

$$\chi_3 \equiv \frac{0.70\,\bar{R}^4}{Cg} \oint\!\!\oint p_s \cos^3\phi \,\mathrm{d}\lambda\,\mathrm{d}\phi + \frac{\bar{R}^3}{\Omega C g} \oint\!\!\oint\!\!\oint u\cos^2\phi\,\mathrm{d}\lambda\,\mathrm{d}\phi\,\mathrm{d}p. \qquad (\mathrm{A}\ 3)$$

The surface and volume integrals are defined as:

$$\oint\!\!\oint (\ )\,\mathrm{d}\lambda\,\mathrm{d}\phi \equiv \int_{-\frac{1}{2}\pi}^{+\frac{1}{2}\pi} \int_0^{2\pi} (\ )\,\mathrm{d}\lambda\,\mathrm{d}\phi,$$

and

$$\oint\!\!\oint\!\!\oint (\ )\,\mathrm{d}\lambda\,\mathrm{d}\phi\,\mathrm{d}p = \int_0^{p_s} \int_{-\frac{1}{2}\pi}^{+\frac{1}{2}\pi} \int_0^{2\pi} (\ )\,\mathrm{d}\lambda\,\mathrm{d}\phi\,\mathrm{d}p. \qquad (\mathrm{A}\ 4)$$

In these expressions, (ϕ, λ) denote latitude and longitude respectively, $p_s(\phi, \lambda, t)$ is the surface pressure, where t denotes time, and $u(\phi, \lambda, p, t)$ and $v(\phi, \lambda, p, t)$ are the eastward and northward components of the wind velocity at pressure level p_0. In the calculations presented here we follow BHWW who took $\bar{R} = 6.37 \times 10^6$ m for the mean radius of the solid Earth, $\Omega = 7.29 \times 10^{-5}$ rad s^{-1} for its mean rotation rate, $g = 9.81$ m s^{-2} for the mean acceleration due to gravity, $C = 7.04 \times 10^{37}$ kg m^2 for the polar moment of inertia of the solid Earth (i.e. crust and mantle) and $(C-A)/C = 0.00333$, where A is the corresponding equatorial moment of inertia. The pressure integral is evaluated between the limits 5×10^3 to 10^5 Pa (50–1000 millibar) rather than 0 to p_s because wind data are available only on specific isobaric levels.

If we define m_i, $i = 1, 2, 3$, as the direction cosines of the rotation axis and ω_i, $i = 1, 2, 3$, as the instantaneous angular velocity of body-fixed axes, x_i, $i = 1, 2, 3$, relative to an inertial frame, then

$$(\omega_1, \omega_2, \omega_3) = (m_1, m_2, 1 + m_3)\,\Omega. \qquad (\mathrm{A}\ 5)$$

If $\Delta\Lambda$ is the difference of the length-of-day $\Lambda \equiv 2\pi/\omega_3$ from its mean value $\Lambda_0 \equiv 2\pi/\Omega$, it follows that

$$m_3 = -\Delta\Lambda/\Lambda_0. \qquad (\mathrm{A}\ 6)$$

From considerations of angular momentum exchange between the atmosphere and solid Earth it can be shown that, so far as the axial component is concerned, $\dot{m}_3+\dot{\chi}_3 = 0$, so that

$$\chi_3 = \Delta \mathit{\Lambda}/\mathit{\Lambda}_0 - \langle \Delta \mathit{\Lambda}/\mathit{\Lambda}_0 \rangle, \qquad \text{(A 7)}$$

where the 'constant' of integration $\langle \Delta \mathit{\Lambda}/\mathit{\Lambda}_0 \rangle$ is chosen so that the curves showing the respective time variations of χ_3 and $\Delta \mathit{\Lambda}/\mathit{\Lambda}_0$ coincide at the beginning of the interval being studied. Inasmuch as non-atmospheric effects, such as core–mantle coupling, changes in surface ice distribution and tidal friction, all act on longer timescales than those due to the atmosphere (as expressed by χ_3), $\langle \Delta \mathit{\Lambda}/\mathit{\Lambda}_0 \rangle$ can be regarded as a very slowly-varying quantity, to be re-assigned every few years. The determination of $\langle \Delta \mathit{\Lambda}/\mathit{\Lambda}_0 \rangle$ in this way will, of course, lead in due course to geophysically important results, but if short-term changes in the length-of-day are due solely to angular momentum exchange between the atmosphere and the solid Earth, then the graphs displayed here of $\chi_3(t)$ and $\Delta \mathit{\Lambda}(t)/\mathit{\Lambda}_0 - \langle \Delta \mathit{\Lambda}/\mathit{\Lambda}_0 \rangle$ should, within the comparatively small errors involved, be identical. The results presented in figures 1 and 2 – produced, together with figures 3 and 4, with the help of Mr R. D. Carter of this laboratory, whose assistance is gratefully acknowledged – show that this is so, thus confirming and extending the results of Hide *et al.* (1980) based on the best meteorological data sets available, and obtained during the limited Special Observing Periods in 1979 of the FGGE.

So far as the dynamics of the excitation of polar motion by fluctuations in the equatorial components χ_1 and χ_2 of χ_i is concerned, it may be shown that if $\boldsymbol{m} \equiv m_1 + \mathrm{i} m_2$ and $\boldsymbol{\chi} \equiv \chi + \mathrm{i}\chi_2$ then

$$\boldsymbol{m} + (\mathrm{i}/\sigma)\,\dot{\boldsymbol{m}} = \boldsymbol{\chi} - (\mathrm{i}/\Omega)\,\dot{\boldsymbol{\chi}} + \langle \boldsymbol{\chi} \rangle + \boldsymbol{\Phi}, \qquad \text{(A 8)}$$

where $2\pi/\sigma$ is the 'observed' Chandler period 435 days, $\langle \boldsymbol{\chi} \rangle$ represents the slowly-varying off-diagonal terms in the inertia tensor of the Earth, the dot denotes the time derivative, and the quantity $\boldsymbol{\Phi}$ includes all damping effects on the wobble. Over time intervals that are much less than the damping period of about 20 years, we can neglect $\boldsymbol{\Phi}$ in (A 8), and to a first approximation we can also neglect the term involving $\dot{\boldsymbol{\chi}}$, since $\dot{\boldsymbol{\chi}}/\Omega$ is typically much smaller in magnitude than $\boldsymbol{\chi}$. The solution of the resulting simplified equation $\boldsymbol{m} + (\mathrm{i}/\sigma)\,\dot{\boldsymbol{m}} = \boldsymbol{\chi}'$ where $\boldsymbol{\chi}' \equiv \boldsymbol{\chi} + \langle \boldsymbol{\chi} \rangle$ is:

$$\boldsymbol{m}(t) = \mathrm{e}^{\mathrm{i}\sigma t}\left[\boldsymbol{m}(t_0) - \mathrm{i}\sigma\left(1+\frac{\sigma}{\Omega}\right)\int_{t_0}^{t} \boldsymbol{\chi}'(\tau)\,\mathrm{e}^{-\mathrm{i}\sigma\tau}\,\mathrm{d}\tau\right] - \frac{\sigma}{\Omega}\left[\boldsymbol{\chi}'(t) - \mathrm{e}^{\mathrm{i}\sigma t}\boldsymbol{\chi}'(t_0)\right], \qquad \text{(A 9)}$$

where $\boldsymbol{m}(t_0) \equiv \boldsymbol{m}(t = t_0)$, and τ is a dummy time variable. In the results presented in figure 4 the observed polar motion $\boldsymbol{m}$[B.I.H.] over an interval of 3.6 Chandlerian periods is compared with the predicted polar motion $\boldsymbol{m}[\boldsymbol{\chi}]$ based on (A 9). The remarkably good agreement between these curves of $\boldsymbol{m}$[B.I.H.] and $\boldsymbol{m}[\boldsymbol{\chi}]$ strengthens the findings of BHWW that, contrary to the conclusions presented by previous workers, polar motion, at least over the interval studied, can be accounted for without invoking substantial excitation by non-meteorological processes.

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Discussion

T. GOLD, F.R.S. (*Space Sciences Building, Cornell University, Ithaca, New York, U.S.A.*). If one were to leave out the damping of the nutation, surely the amplitude would increase indefinitely in a statistical way. In turn, if one can identify the exciting force, one can deduce eventually what the damping factor must be. Without knowing the exciting function in detail, one could still gain some knowledge of the damping factor from the ratio of the irregular to the regular amplitude of the observed nutation.

R. HIDE. Professor Gold is quite correct. I was not able to discuss these details in the short time available for the presentation of these results, but the printed version of the paper will make clear how by continuing to calculate atmospheric excitation of changes in the length of the day and polar motion in the way described, it will be possible to determine effects due to damping and to excitation by non-meteorological processes.