THE POSSIBILITY OF ESTIMATING TIDAL PERTURBATIONS OF JUPITER'S GALILEAN SATELLITES.

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ABSTRACT. Recent measurements in the infra-red of the energy emitted by Io suggest that if the observed emission is due to tidal dissipation in Io, then one should observe a very large secular acceleration of Io in its orbit. The purpose of this paper is to investigate the observational evidence which might be examined to verify that hypothesis. We have assembled the largest collection of eclipse observations extant and investigate the possibility of observing secular drifts in the period of Io. Analysis of eclipse observations requires the knowledge of good tables of ΔT and we explore the implications of the standard lunar acceleration of Spencer-Jones $\dot{n}_{Moon} = -22.44$ arcsec/cy^2 versus that of Morrison and Ward $\dot{n}_{Moon} = -26.0$ arcsec/cy^2. Preliminary results suggest that large tidal accelerations of Jupiter's satellites do not exist at the suggested magnitude and hence the heat flux measurements probably represent an episodic occurrence.

1. INTRODUCTION

The relativistic effects of Jupiter are on the order of meters. Before one can investigate them he must be able to handle effects which are of a larger magnitude. One such effect is the possible influence of tidal dissipation on Jupiter's satellites. The several areas of astronomy which appear in the study of the evolution of the Galilean satellite system involve both modern and classical observations, celestial mechanics and the influence of our understanding of modern reference systems.

I will concentrate on a "modern" problem which shows the interdependence of these various areas on each other and how progress in any one area is dependent upon progress in understanding of other areas of "fundamental" astronomy. The example concerns the tidal dissipation of energy within the Jupiter system and how that dissipation depends upon, and also influences, the orbital properties such as resonances and eccentricities.

2. GALILEAN SATELLITES AND TIDAL INTERACTIONS

The Galilean satellites have periods which are approximately in the ratio of 1 : 2 : 4 : 8 and those ratios produce resonances which affect the motion of the satellites. The well-known Laplace libration, for example, involves the inner three satellites and it restricts their relative positions so that if one takes the longitude of Io minus three times the longitude of Europa plus twice the longitude of Ganymede, then that sum will

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be 180 degrees plus a small libration, on the order of 0.07 degrees. The amplitude of the Laplace libration is important in evaluating the evolution of the system—essentially it is exponentially damped and its current residual value could be used as an indicator of the age of the system.

One can discuss the 3-body Laplace libration as a "lock" involving the three inner satellites

$$n_1 - 3n_2 + 2n_3 = 0 \tag{1}$$

—or as two two-body constraints:

$$\begin{aligned} n_1 - 2n_2 &= \nu \\ n_2 - 2n_3 &= \nu, \end{aligned} \tag{2}$$

where the value $n_1 - 2n_2$ has a motion of about 3/4 degree per day.

The physical effect of tides raised by Io on Jupiter are such that Jupiter (which rotates faster than Io moves in its orbit) has a tidal bulge due to Io and that tidal bulge tends to force Io farther away from Jupiter so that the mean motion of Io decreases with time. The tides raised by Jupiter on Io, on the other hand, tend to have the opposite effect.

Based upon the work of Kaula (1964) and that of Yoder and Peale (1981), we can derive an equation which gives the rate of change of Io's mean motion as a function of the tidal dissipation in Jupiter and as a function of the tides raised by Jupiter on Io:

$$\frac{\dot{n}_1}{n_1} = -\frac{c}{Q_J}\left[1 - \frac{D}{8500}\right] \tag{3}$$

where $c \approx 6 \cdot 10^{-13} sec^{-1}$ and where D is the ratio of Io tides to Jupiter tides.

Of great interest to physicists is the tidal dissipation factor Q_J, which yields information about the internal dissipation of tides within Jupiter. If one takes into account the effect of the Laplace resonance-lock, then according to Yoder (1979) and to Yoder and Peale (1981) there is an additional equation which relates the tidal evolution in mean motion between Io and Europa:

$$\dot{\nu} = \dot{n}_1 - 2\dot{n}_2 = -\frac{cn_1}{3Q_J}\left[1 - \frac{D}{4600}\right]. \tag{4}$$

If, for example, one assumed that Io and Europa were in a quasi-stationary state (that is that their mean motions moved out together so that $n_1 \approx 2n_2 \approx 4n_4$ always), then one can determine the ratio D of tides raised by Jupiter on Io to that of tides raised by Io on Jupiter.

What information do we have on the tidally-induced secular change in mean motion or periods? If one takes the modern heat flux measurements of Io as representative of the energy dissipated by tidal heating, then one can predict some effects on orbital evolution and one can then examine existing data to search for such effects. Current heat flux measurements in the infra-red region indicate an average heat flux of about 1.5 watt/meter^2 (Matson et al., 1981; Sinton, 1981; Pearl and Sinton, 1981; Morrison and Telesco, 1980). If the heat flux measurements are due to tidal interactions, then that implies that the energy being released by tidal friction is on the order of 6.2 x 10^{13} watt.

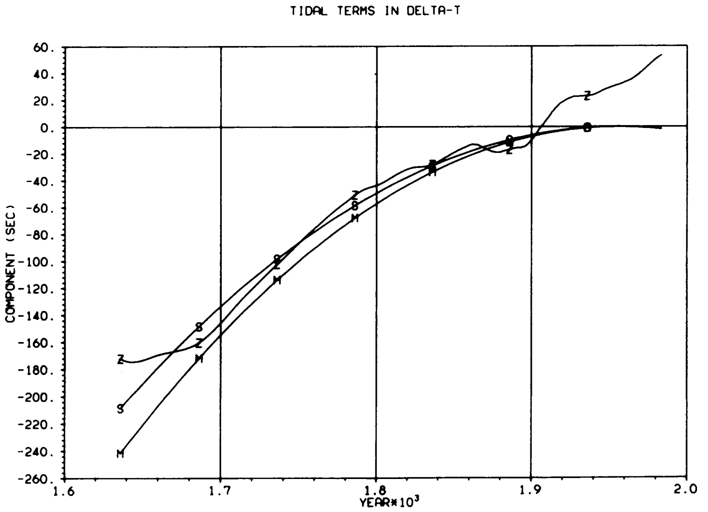

Figure 1. Plot of effects of $\dot{n}_{Moon}$ on ΔT. Z is the curve, based upon Morrison's ΔT data which would represent the "observed" $\Delta T = ET - UT$ if there were no lunar tidal acceleration. The curve S represents the effect of Spencer-Jones' $\dot{n}_{Moon} = -22.44$ arcsec/cy^2 and the curve M represents that using Morrison and Ward's $\dot{n}_{Moon} = -26.0$ arcsec/cy^2. The derived value of ΔT is obtained from $\Delta T(Spencer - Jones) = Z - S$ or $\Delta T(Morrison) = Z - M$.

An estimate of the effect such an energy dissipation should have upon the orbital evolution can be obtained as follows. If we assume that the currently observed heat flux on Io represents the tidally-induced energy loss, and if we assume that the orbits are quasi-stationary and uniformly expanding with time while maintaining the 3-body lock given in Eq. (1), then the energy dissipated in Io comes from the orbital energy of the three inner satellites, rather than just from Io alone. About half the inner-three-satellite-system energy resides in Io. Hence if we estimate the change in mean motion induced by the heat loss, we find that Io's mean motion changes about a factor of two less than it would if there were no resonance.

Based upon the heat flux measurements, according to Yoder and Peale we would expect the mean motion of Io to show a secular acceleration of $-299\ ''T^2$, *viz.* about 10 times that experienced by our Moon due to tidal dissipation. This effect then should show up in the longitude of Io as a term of about $-150\ ''T^2$, and hence eclipse residuals ought to show the effect as a timing error of something like -18 T^2 sec. That would amount to a drift of about 160 seconds in three centuries—an effect which should be observable. As we will later see, such a large effect is not visible in the data.

3. CONSIDERATION OF ΔT

In order to obtain realistic estimates of the tidally-induced secular acceleration of Io's mean motion, we must consider other sources of error. The eclipse timings, which are observed on Earth, introduce the effects of problems involving ΔT, the difference between Ephemeris and Universal times. The eclipses as observed from the Earth are generally observed in UT while the predictions of when a satellite enters Jupiter's shadow are calculated in ET.

Nowadays we can effectively observe both Universal Time and Ephemeris Time. Prior to the era of atomic clocks, however, we had no direct means of "observing" ET. Instead, we had to determine ΔT by using the Moon as an intermediary. Effectively the process worked as follows: As now, we "observe" UT via stellar transits and we observe occulations of stars by the Moon; we assume that some lunar ephemeris is perfect on an ET scale. By then comparing the observed times with the predicted times we can derive a lunar-based value for ΔT.

As an example, suppose that we assumed that there were *no* tidal acceleration model for the Moon. Then from occultations we could derive the expression ΔZ, which would represent the difference between "Ephemeris-Time with no lunar tidal acceleration" and UT. A plot of such an "observed" function, based upon the work of L. Morrison (1980), is shown in Fig. 1 as the curve Z.

If on the other hand, we adopted some model for the tidal acceleration of the Moon, then our value of ΔT depends upon the "observed" ΔZ as well as upon our adopted value for the rate of change of the lunar motion [see, *e.g.* Stumpff and Lieske (1984)]. The value of ΔT is obtained from ΔZ minus the adopted value for lunar tidal dissipation [e.g. S for the Spencer-Jones (1939) value as employed by Brouwer (1952) or M for the Morrison and Ward (1975) value of $\dot{n}_{Moon}$.]

Table 1. Recently determined values of $\dot{n}_{Moon}$ $(arcsec/cy^2)$

$\dot{n}_{Moon}$	Author	Reference
-22.44 ± 1	Spencer Jones	*Mon. Not. R. Astron. Soc.* **99**, 541 (1939)
	Clemence	*Astron. J.* **53**, 169 (1948)
$-26. \pm 2$	Morrison and Ward	*Mon. Not. R. Astron. Soc.* **173**, 183 (1975)
-25.3 ± 1.2	Dickey et al.	*IUGG/IAG Hamburg* (1983)
-22.9 ± 0.8	Krasinsky, et al.	*Astron. Astrophys.* **145**, 90 (1985)
-22.2 ± 0.8	Krasinsky, et al.	*Astron. Astrophys.* **145**, 90 (1985)
-38 ± 8	Oesterwinter & Cohen	*Celest. Mech.* **5**, 317 (1972)
-36 ± 10	van Flandern	*Mon. Not. R. Astron. Soc.* **170**, 353 (1975)
-42 ± 6	Morrison, L.	*Nature* **241**, 519 (1973)

How well do we know the rate of change of the lunar mean motion? In Table 1 I summarize the current status of that field of astronomy. It has only been in the last several years that investigators have begun to obtain consistency in their results. In the early 1970s, for example, the observationally-derived lunar tidal term $\dot{n}_{Moon}$ varied by more than a factor of two. Since the Moon moves about 0.5 arcsec in 1 second of time, one can estimate the variation in ΔT by taking the difference between two values of $\dot{n}_{Moon}$ given in seconds of arc. The difference between the Spencer-Jones value of $\dot{n}_{Moon}$ versus the Oesterwinter value amounts to something on the order of 16 s T^2—very, very large, and on the order of size as the "predicted" effect of the heat flux measurements on

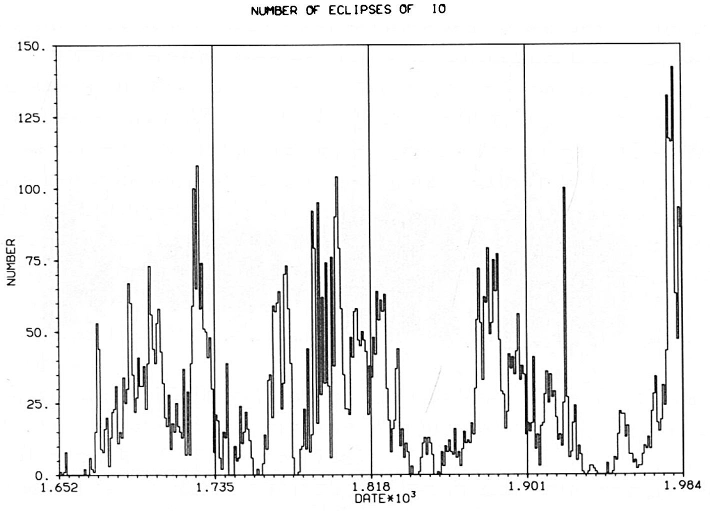

Figure 2. Histogram depicting the number of eclipse observations of Io that are contained in the collection as a function of the year.

Io. Fortunately, nowadays everyone seems to be deriving a value somewhere between the Spencer-Jones determination of $\dot{n}_{Moon} = -22.44$ and Morrison and Ward's $\dot{n}_{Moon} = -26$.

If we assume that the "real" ΔT lies between the Spencer-Jones and Morrison tidal acceleration models for $\dot{n}_{Moon}$, then we can draw two x-axes which represent $y = 0$ (*i.e.*, zero residuals) for the two cases. As we will see, such a curve will be useful for evaluating a value for the tidally-induced acceleration of Io.

4. THE OBSERVATIONAL DATA: BACKGROUND

Prior to the Voyager mission, the ephemerides of the Galilean satellites were derived from earth-based observations of eclipses, mutual events and photographic data (Lieske, 1980). The data spanned approximately 100 years and the ephemerides have been labeled E-2. These ephemerides were used by the Voyager mission and proved to be accurate to within 100-200 km.

Since the time of the Voyager mission, we have greatly extended the observational data base and now have more than 16000 eclipse observations since the mid 1600s. If we desire to study ΔT or tidal effects from observations of Io, then we can't do much with just 100 years of data, as is seen in the overlay depicting the axis of zero residuals for Morrison's $\dot{n}_{Moon}$.

It generally has been assumed that Delambre collected about 5500 eclipses prior to about 1815 and that those have been lost. Earlier in this century, Sampson (1910) "re-discovered" the computer-records of the Europa data that Delambre presumably used, and more recently Arlot et al. (1984) found some "computer records" for Io. But it was not until two remarkable treasures were re-discovered that we were able to effectively re-assemble the great Delambre collection. A book on 17th century astronomy by Pingré, published by the Paris Academy in 1901 by Bigourdan (1901), was originally scheduled for publication 100 years earlier by Pingré. But Pingré's death and the French revolution intervened, and the printer's proof copies were destroyed as scrap paper. It was only 100

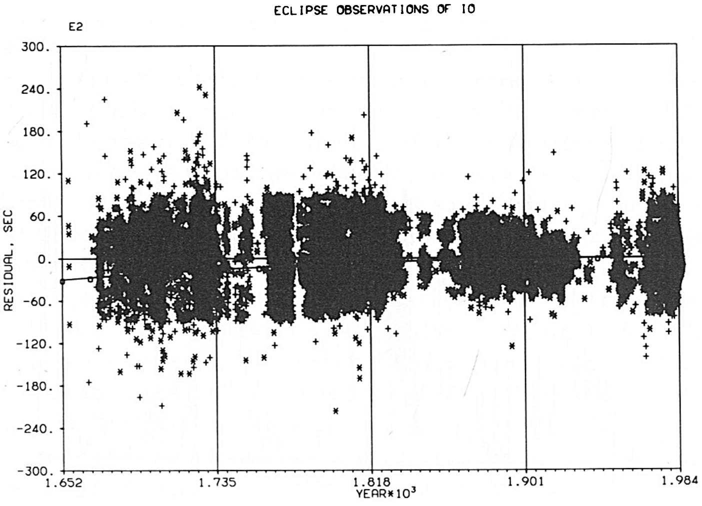

Figure 3. Plot of Observed minus Calculated times of eclipse (in sec) using Ephemeris E-2 for Io from 1652 to 1983. Residuals in sec may be converted to longitude residuals in km by multiplication by -18 km/s. No adjustments to the E-2 ephemeris have been made. The x-axis for zero-residuals for Morrison's values of ΔT and his $\dot{n}_{Moon} = -26.0$ are depicted by the solid curve.

years later that a copy of the proofs was found and ultimately published by the Paris Academy.

Another treasure, which was probably the "mother-lode" for Pingré's work, is the manuscript collection of J.-N. Delisle (Bigourdan, 1897). Delisle worked in St. Petersburg from 1725 to 1747 and amassed a great manuscript collection of eclipse observations. This collection still exists in Paris but at the time of the French revolution it was mis-filed. Largely based upon these two collections, as well as Bode's *Astronomisches Jahrbuch,* we now have more than 7200 eclipse observations prior to 1800.

5. ECLIPSE OBSERVATIONS

A histogram showing the distribution of observations of Io as a function of year is given in Fig. 2. In a small way this plot is a record of scientific and world history. The early observations were a direct result of the development of the pendulum clock by Huygens and by the founding of the Paris Observatory in 1668 and the founding of the Greenwich Observatory. The early interest in using Io for longitude determinatins is clearly evident, and the peak in the mid 1670s represent the Picard-Roemer series from which Roemer determined the finite speed of light. It is seen that interest grew after Newton published his *Principia*, and the large peak indicating Delisle's interest and the founding of the Academy in St. Petersburg is also quite evident. The effects of international affairs such as wars are also apparent. There is a significant drop-off in data at the time of Bode's retirement as editor of the *Astronomisches Jahrbuch,* since his successor Encke did not publish current observations. The renewal of interest in observational astronomy as a result of the Space Age is also evident, as well as the significant interest expressed by amateur observers who today produce the bulk of the observational material.

If we plot the residuals of all 16000 eclipses which we have thus far collected on Ephemeris E-2 (in other words, we have made no adjustments to the orbits), then the plots for Io appear as in Fig. 3, if we use the Spencer-Jones $\dot{n}_{Moon} = -22.44$ value of lunar tidal acceleration with Morrison's basic ΔT values. The curves are remarkably flat and indicate that there are no major errors in the satellite ephemerides. We will use these data to improve the ephemerides for the upcoming Galileo mission, but they are already quite good. If we adopt Morrison's ΔT value, then the new x-axis would appear as shown by the solid line, amounting to about -30 s for the early data. There may or may not be a tendency for the data to follow the Morrison curve, but it certainly does not follow the curve that we would expect as a result of the recent heat flux measurements. The obvious conclusion is that the heat flux measurements are either episodic or that they are not due to tides.

We now have about 16000 eclipses of the satellites since 1652, when Hodierna in Sicily made the first reliable eclipse timings. We have about 8500 observations of I, 4000 of II, 2400 of III and 900 of IV (Lieske, 1985).

So these old eclipses will be invaluable (and in fact are the only means of estimating some physical parameters of interest) in developing ephemerides of the Galilean satellites for the next space missions, for historians of science, and for the evaluation of competing physical hypotheses on the evolution of the system.

Table 2. Preliminary values of Jupiter's pole parameters

Author	Method	$\alpha_J(degrees)$	$\delta_J(degrees)$
Null (1976)	Pioneer 10, 11	267.998 ± 0.016	64.504 ± 0.004
Campbell and Synnott (1985)	Pioneer 10, 11; Voyager 1, 2	268.001 ± 0.005	64.504 ± 0.001
This study	Earth-based	268.002 ± 0.006	64.503 ± 0.001

Table 3. Preliminary values of satellite masses GM (km^3/sec^2)

Author	Method	Io	Europa	Ganymede	Callisto
Null (1976)	Pioneer 10, 11	5934 ± 28	3196 ± 32	9885 ± 37	7172 ± 24
Campbell and Synnott (1985)	Pioneer 10, 11; Voyager 1, 2	5961 ± 10	3201 ± 10	9887 ± 3	7181 ± 3
This study	Earth-based	5878 ± 25	3222 ± 13	9898 ± 20	7245 ± 68
Sampson (1921)	Earth-based	5697	3204	10120	5706

6. PRELIMINARY RESULTS

In order to get an indication of the power and accuracy of these earth-based measurements (eclipses, mutual events, photographic data) relative to space-craft determined values, I have made some preliminary solutions (without using the Voyager data).

In the case of Jupiter's pole, for example, the results are given in Table 2. The modern standard [due to Null (1976) who analyzed Pioneer data] is in agreement with that determined solely from earth-based observations. I also give the results of Campbell and Synnott (1985), who employed Voyager data along with constraints from Pioneer and earth-based observations. As one can see, the classical earth-based data are quite powerful and justly deserve their influence in modern astronomy.

Preliminary values of the masses are given in Table 3. By comparison, the results of Sampson are clearly significantly different. The result which I would like to stress here is how complementary the modern and classical results are with one another.

I will later combine the earth- and spacecraft-based data in order to derive the best values, but already it appears that the modern and the classical methods both offer complementary strengths.

In summary, from this little example involving the Galilean satellites of Jupiter, I have tried to demonstrate how various areas of astronomy all play an important role in lending progress to our quest for understanding of the nature of the universe. I think that the classical methods still play an important role and that the modern re-birth of those methods in such experiments as HIPPARCOS and Space Telescope will provide us with further needed information.

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DISCUSSION

Nobili : Yoder derives the acceleration of Io from the observed infra-red flux. How does the value of the tidal dissipation coefficient Q of Jupiter influence his results ?

Lieske : Yoder and Peale estimated the tidal effect in longitude by adopting a mean value for the energy observed in the infrared measurements and by assuming that this energy was due to tidal dissipation. The energy must come from the orbital energy and hence they derived the value of $dn/dt = -300''t^2$. It would correspond to Q = 50 000 which is a very low value. The values shown in figure 3 for Io suggest that Q would be of the order of 10^6 if one uses the value of (dn/dt) Moon between the Spencer Jones and Morrison results. In other words, we do not see a large tidal effect on the satellites.

Kozai : I understand that secular accelerations have been detected in the motion of the fifth satellite of Jupiter. Do you think that this is due to tidal perturbations ?

Lieske : in our ephemeris developments for the Voyager mission, I do not recall any significant secular acceleration that was determined for Amalthea from our analysis of Earth-based data. Since the Earth-based data are generally taken only at elongations and since the satellite has not been observed for as long a period as the Galilean satellites, then I believe that tidal effects could not readily be estimated from Amalthea observations.