LECTURE 1

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A Correction to the Gravitational Model

Alexander Franklin Mayer

www.stanford.edu/~afmayer

www.alexadermayer.com

← Use your arrow keys to page through the lecture. →
Press esc (escape) to exit the full-screen mode.

Theoretical physics criteria

- Simplicity
- Elegance
- First principles
- Empirical proof

If a physical theory does not meet these criteria, then something is wrong or the entire approach to the subject under investigation is misguided.

General Relativity (GR)

- The empirical verifications indicate that a metric theory was clearly the right idea.
- GR's incompatibility with quantum mechanics implies that the theory is somehow lacking.
- Just the complexity of the relationships (mathematics), alone, makes it suspect.

In this lecture we are going to make GR simpler and more elegant, bring it closer to first principles, and explain observed gravitational phenomena such as planetary migration and the Pioneer Anomaly.

The foundation of GR

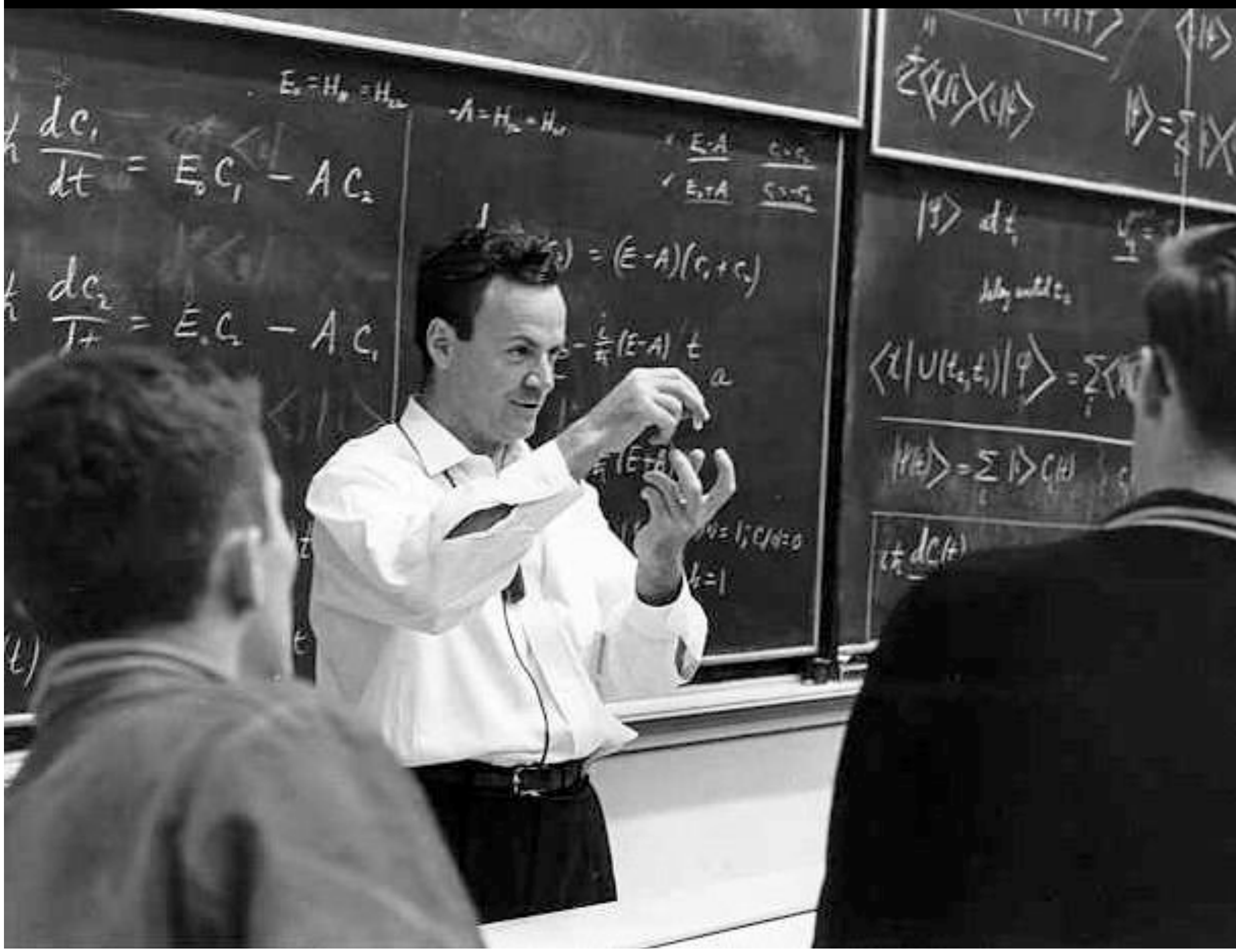
- SR: The locally measured speed of light in vacuum is constant.
- EEP: within a neighborhood of any freefalling region, SR holds.

SR – Special Relativity
EEP – Einstein Equivalence Principle

Nature has a great simplicity and therefore a great beauty.
–Richard Feynman

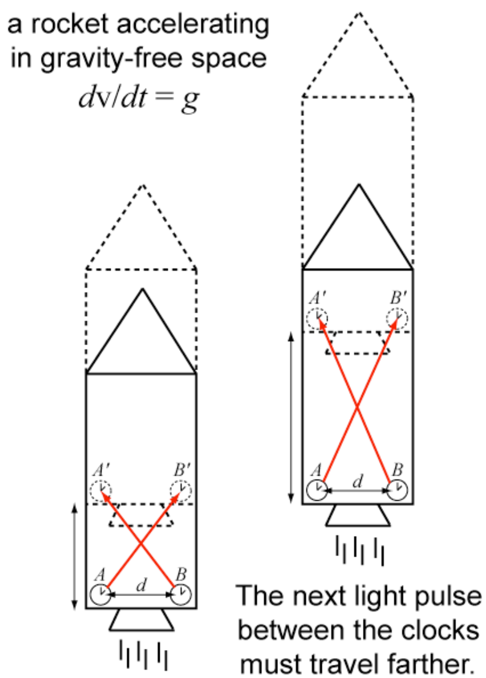
Science alone of all the subjects contains within itself the lesson of the danger of belief in the infallibility of the greatest teachers in the preceding generation. . . . Learn from science that you must doubt the experts. As a matter of fact, I can also define science another way: Science is the belief in the ignorance of experts.

Richard Feynman, *The Pleasure of Finding Things Out*, (Perseus Books, New York, 1999), pp. 186-187.



A simple thought experiment

- Ideal clocks A and B, separated by a fixed distance d on the same 'floor' of the spacecraft, send out a pulse of light for each 'tick' of the clock.



- According to an inertial observer, the distance light must travel between the two ideal clocks A and B must increase for each subsequent 'tick' of a clock.
- The incurred extra time delay for each subsequent pulse to arrive implies that the rate at which pulses are received is less than the rate at which they are produced.

Unequivocal implications

- An accelerated observer at A perceives the period of clock B to decrease in proportion to the acceleration of the spacecraft.
- The effect is symmetric: A to B and B to A.
- Electromagnetic radiation redshifts over a path *transverse* to the direction of the reference frame’s acceleration (the line from A to B).
- Numerous empirical observations imply that this effect does, of course, occur.

When we are ‘sure’ of something based on an equation that is found to contradict first principles, we are almost certainly unaware of false assumptions associated with that equation.

The effect is very small

- The travel time of a photon is d/c.
- The Δv in this time is gd/c.
- The transverse redshift effect is not measurable in the laboratory.

$$\omega \approx \omega_0 \sqrt{1 - \frac{g^2 d^2}{c^4}} \qquad c^4 \sim 10^{34} m^4 s^{-4}$$

EEP

- If a transverse redshift effect occurs for inertial acceleration, then EEP implies that it occurs in a gravitational field.
- The effect is clearly too small to measure in a laboratory experiment, e.g., Mössbauer effect.
- Look for unmodeled GPS PR (pseudo range) residuals and and unexpected results of spacecraft radio science experiments…

GPS clock errors

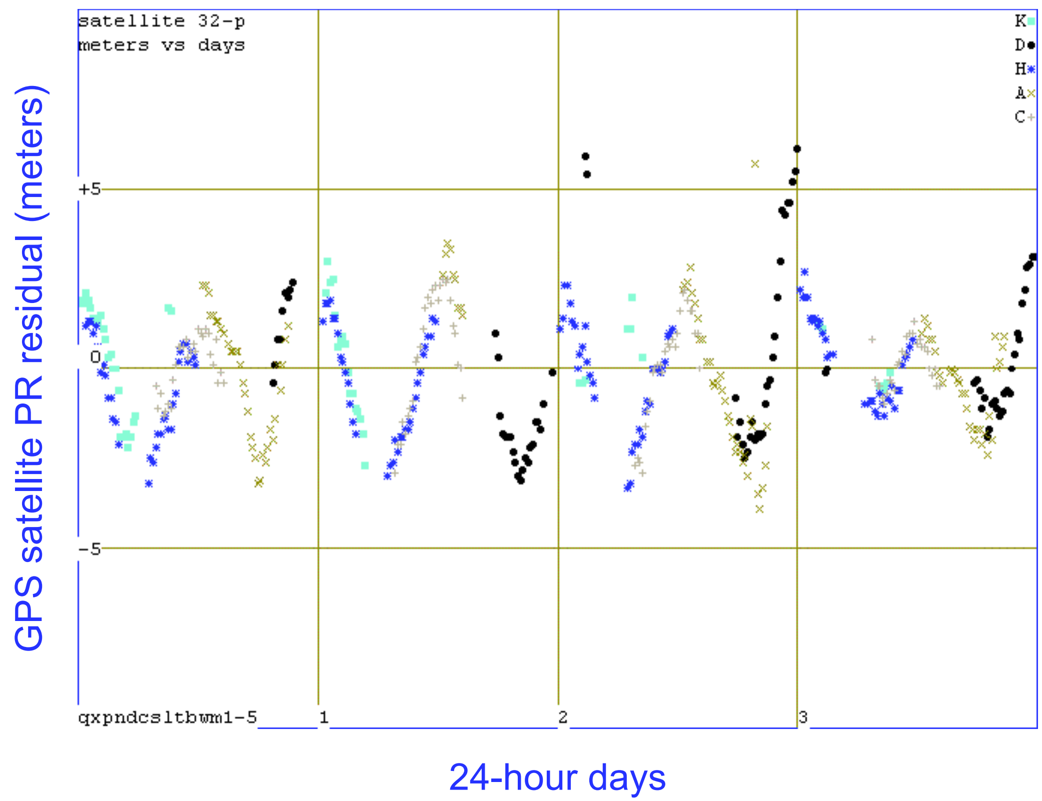
The principle reason for investigating in detail relativistic effects is to improve the current accuracy of GPS and to create future time transfer and navigation systems that have several orders of magnitude better accuracy. At the present time, it is well-known that small anomalies exist in position and time computed from GPS data. The origin of these anomalies is not understood. In particular, GPS time transfer data from the U.S. Naval Observatory indicates that GPS time is periodic with respect to the Master Clock, which is the most accurate source of official time for the U.S. Department of Defense [14–16]. Furthermore, other anomalies have been found in Air Force monitor station data that are not understood at present [17].

Thomas B. Bahder, “Fermi Coordinates of an Observer Moving in a Circle in Minkowski Space: Apparent Behavior of Clocks”, (Army Research Laboratory, Adelphi, Maryland 2005); arXiv: gr-qc/9811009.

Continued…

GPS PR (pseudo-range) residuals

- This semidiurnal saw-toothed pattern is the effect we would expect to see if there were an unmodeled transverse redshift.
- The effect is a minimum when the satellite transits a station and a maximum when the satellite is near the horizon.



Thomas Van Flandern & C. O. Alley, "Absolute GPS to better than one meter", unpublished, Meta Research, (12 February 1997). Reproduced with permission.

Science, 1962

Abstract. *Two experiments are described where an apparent decrease in frequency was detected when the optical path was in the vicinity of a mass. In the first experiment the 21-centimeter absorption line from Taurus A was observed near occultation by the sun. In the second experiment the frequency of a portable cesium clock was compared with the frequency of a similar clock which transmits its signals from Cape Fear, North Carolina. A decrease of frequency of the received signals as a function of the distance between the two clocks was apparent. Several relevant observations (the red shift of lines from the sun, the Mössbauer determination of the gravitational redshift, and the cosmological red shift are discussed in view of the present results.*

...

We are aware of the enormous theoretical difficulties implied by the apparent results and of the need to seek further confirmation.

E. O. Hulbert Center for Space Research,
Naval Research Laboratory, Washington, D.C.

Dror Sadeh, Stephen Knowles & Benjamin Au, “The Effect of Mass on Frequency”, *Science* **161**, 567-569 (1962).

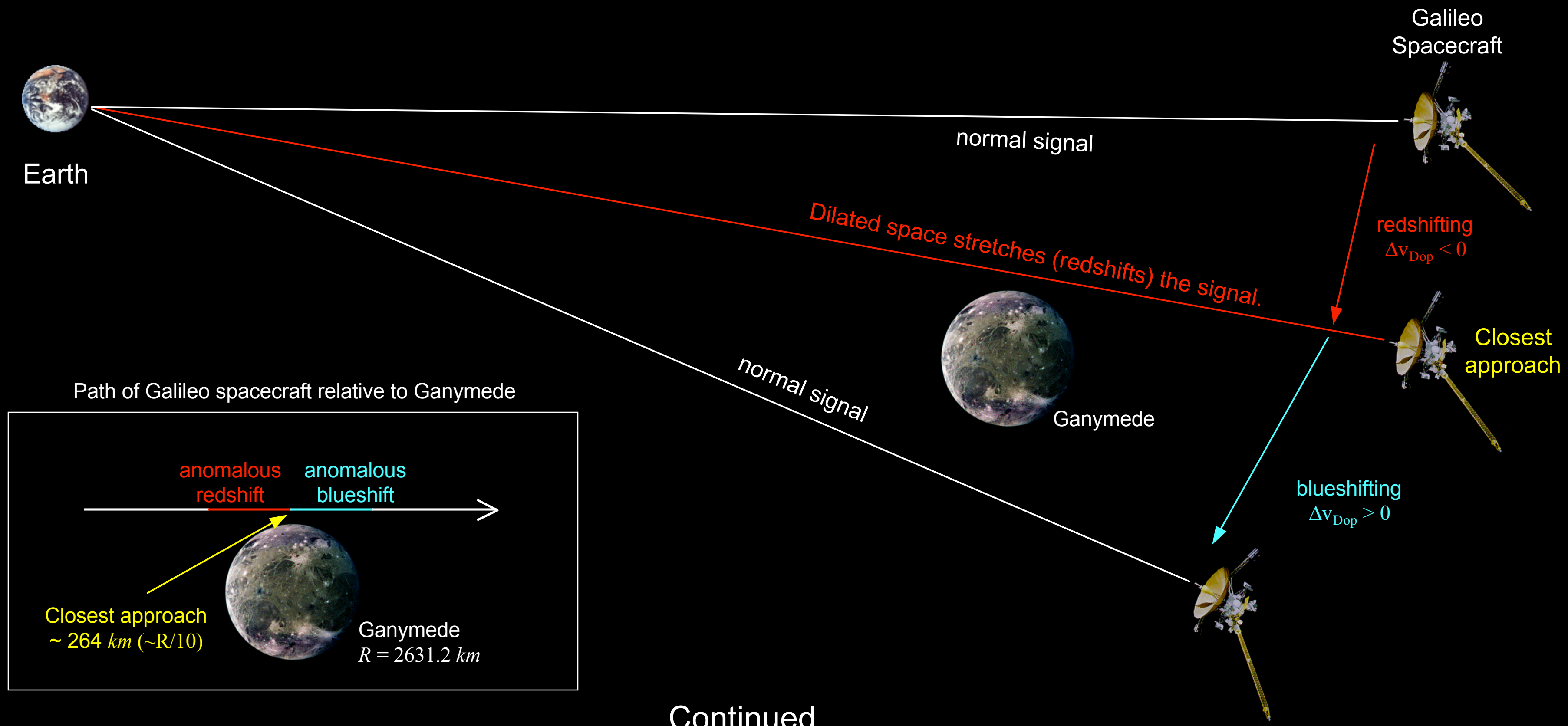
Procedures have been developed which attempt to excise corrupted data on the basis of objective criteria. There is always a temptation to eliminate data that is not well explained by existing models, to thereby “improve” the agreement between theory and experiment. Such an approach may, of course, eliminate the very data that would indicate deficiencies in the a priori model. This would preclude the discovery of improved models.

John D. Anderson *et al.*, “Study of the anomalous acceleration of Pioneer-10 and 11”, *Physical Review D* **65**, 082004-9 (2002).

A radio science experiment

The proposed unmodeled relativistic effect of the gravitational field and the 1962 empirical observations published in *Science* suggest is that if you were to do a modern experiment such as the one depicted in this diagram, there would be a signal modulation that is unmodeled by Einstein's general theory of relativity. As the spacecraft approached Jupiter's moon Ganymede (the largest moon in the Solar System, larger in radius than the planet Mercury and with a mass double that of Earth's Moon) there would be an unmodeled redshift in the telemetry and as you departed there would be a blueshift…

This is an illustrative schematic only and so is not an accurate portrayal of the actual spacecraft ephemeris.



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DSN 70-meter dish

The measurable is the Doppler shift of the radio signal, which very precisely indicates the relative velocity of the spacecraft in reference to the Deep Space Network (DSN) station on Earth monitoring the signal. The redshift would mimic the effect as if the spacecraft were suddenly moving away from the Earth faster and the blueshift would mimic the opposite effect. One possible interpretation of the observable is that the gravitational field causing the ‘acceleration’ is not symmetric because of a mass anisotropy. However, one would expect to see other evidence of this, such as a large geographic feature or a wobble associated with the spin of Ganymede.

Image: NASA, JPL/Caltech

Continued…

Science, 2004

Discovery of Mass Anomalies on Ganymede

John D. Anderson,[1] Gerald Schubert,[2,3] Robert A. Jacobson,[1] Eunice L. Lau,[1] William B. Moore,[2] Jennifer L. Palguta[2]

We present the discovery of mass anomalies on Ganymede, Jupiter's third and largest Galilean satellite. This discovery is surprising for such a large icy satellite. We used the radio Doppler data generated with the Galileo spacecraft during its second encounter with Ganymede on 6 September 1996 to model the mass anomalies. Two surface mass anomalies, one a positive mass at high latitude and the other a negative mass at low latitude, can explain the data. There are no obvious geological features that can be identified with the anomalies.

[1] Jet Propulsion Laboratory, California Institute of Technology
[2] Department of Earth and Space Sciences, University of California, Los Angeles
[3] Institute of Geophysics and Planetary Physics, Los Angeles

John D. Anderson *et al.,* "Discovery of Mass Anomalies on Ganymede",
Science **305**, 989-991 (2004).

The Einstein field equations

- The Gravitational Transverse Redshift (GTR) effect is implied by first principles and is empirically observed.
- The Einstein field equations do not model this effect, so are they flawed?
- If the field equations are flawed, where did Einstein make his mistake?

The genesis of GR

The treatment of the uniformly rotating rigid body seems to me to be very important because of an extension of the relativity principle to uniformly rotating systems by trains of thought which I attempted to pursue for uniformly accelerated translation…

Albert Einstein, Letter to A. Sommerfeld, 29 September, 1909;
Abraham Pais, *Subtle is the Lord… The Science and the Life of Albert Einstein*, (Oxford U. Press, Oxford, 1982), p. 189.

With a measuring-rod at rest relatively to [the rotating system] K', the quotient would be greater than π. This is readily understood if we envisage the whole process of measuring from the "stationary" system K, and take into consideration that the measuring-rod applied to the periphery undergoes a Lorentzian contraction, while the one applied along the radius does not. Hence Euclidean geometry does not apply to K'.

Albert Einstein, "Die Grundlage de allgemeinen Relativitätstheorie", *Annalen der Physik* **49** (1916);
The Principle of Relativity, (Dover Publications, New York, 1952) p. 116.

In a system of reference rotating relatively to an inertial system, the laws of disposition of rigid bodies do not correspond to the rules of Euclidean geometry on account of the Lorentz contraction; thus if we admit non-inertial systems on an equal footing, we must abandon Euclidean geometry. Without the above interpretation the decisive step in the transition to generally covariant equations would certainly not have been taken.

Albert Einstein, "*Geometrie und Erfahrung"*, Lecture before the Prussian Academy of Sciences, 27 January (1921); *Ideas and Opinions*, (Wings Books, New York, 1954) p. 235.

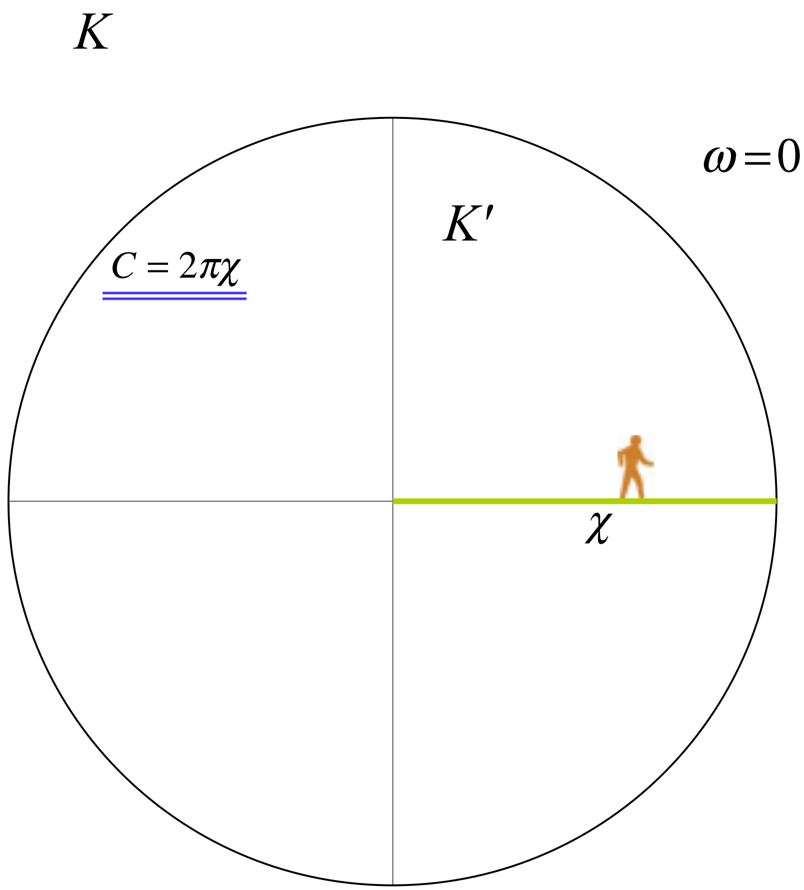
But perhaps Newton's law of field could be replaced by another that holds with respect to a "rotating" system of coordinates? My conviction of the identity of inertial and gravitational mass aroused within me the feelings of absolute confidence in the correctness of this interpretation.

Albert Einstein, "Prof. Einstein's Lecture at King's College, London, and the University of Manchester", *Nature*, **106**, 703 (1921).

A rotating coordinate system

- Ehrenfest’s rotating ‘rigid disk’ is simplistic, naïve, and conceptually deceptive.
- Instead, rotate a Minkowski manifold around the imaginary time axis.
- Any plane of the system within the boundary of a fixed coordinate radius is a ‘rigid disk’.
- A radial beam of light defines a null geodesic (a spatial interval).
- The light beam must obviously curve relative to a rotating coordinate radius.

The inertial frame



The 'rigid disk' K' at rest in inertial frame K.

All length-measurements in physics constitute practical geometry in this sense, so, too, do geodetic and astronomical length measurements, if one utilizes the empirical law that light is propagated in a straight line, and indeed in a straight line in the sense of practical geometry.

–Albert Einstein [1]

The shortest possible route from the center of the disk to its perimeter is along a path that is guided by a radial beam of light (green line). According to the principles of relativity, the physical distance or *spatial interval* between two points is defined in every reference frame as the path of light or the 'null geodesic' (ds=0) between these points.—The *coordinate radius* is an independent geometric object associated with a particular coordinate system. In the *special case* when K' does not rotate, this coordinate radius (χ) is identical to the physical radius (the null geodesic).

1. Albert Einstein, "Geometrie und Erfahrung, Lecture before the Prussian Academy of Sciences", (27 January 1921), *Ideas and Opinions*, (Wings Books, New York, 1954), p. 235.

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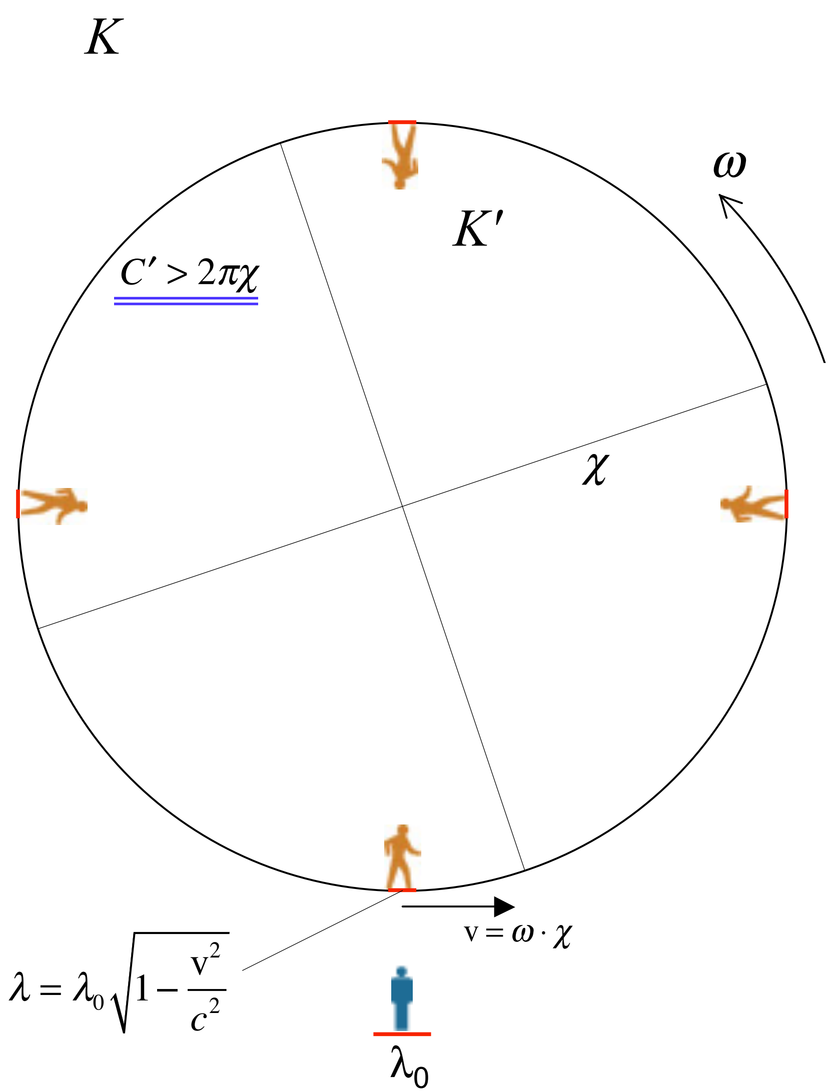
The accelerated frame



Due to the tangential velocity (v) of the 'disk', the inertial observer finds that a measuring-rod (λ_0) fixed to the perimeter is relativistically contracted according to the principles of special relativity due to its relative motion. Accordingly, a greater number of these contracted rods (λ) fits around the circumference of the disk in reference to the inertial frame than the rods of proper length. The distance around the circumference of the disk that is measured by the accelerated observer must be this same number of rods, but they are of proper length when they are at relative rest in K'. Therefore, as correctly determined by Ehrenfest and Einstein, the spatial circumference C' of the rotating disk is measured to be *greater* than the spatial circumference C of the inertial disk.

It follows that the C' is greater than $2\pi\chi$, which gave Ehrenfest and Einstein the idea that the geometry of the disk is non-Euclidean or 'curved' in a peculiar kind of way.—

Unlike pure mathematics, physics is always about *things that can be measured*, so it is important that we think about how "the radius of the disk" is measured when the disk is rotating.

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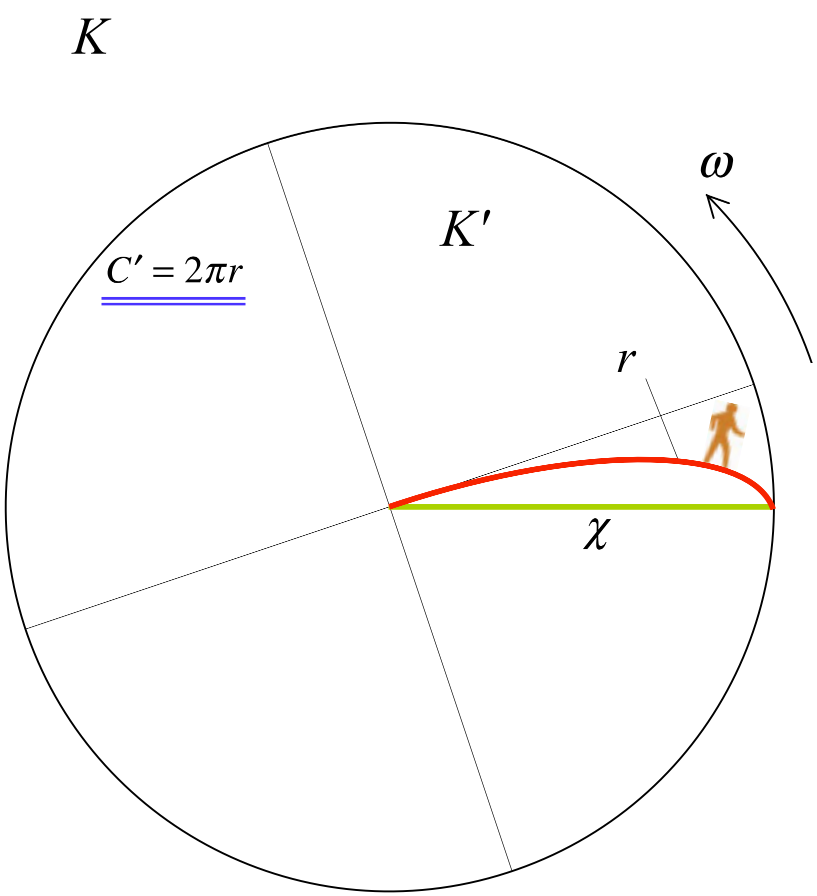
The radius of the accelerated frame

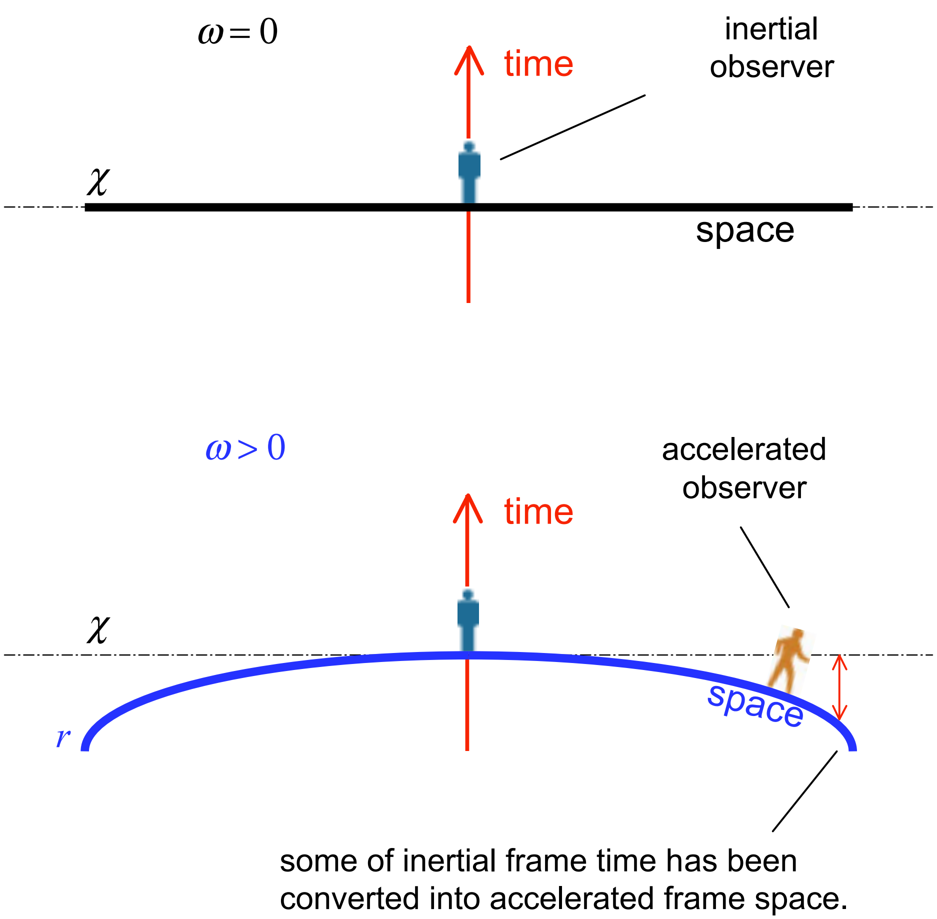


The exaggerated curvature in the red radial light beam for an abstract rotating system of coordinates illustrates a physical principle that holds true for any rotation speed of a plane coordinate 'disk'.

From overhead, an inertial observer sees a photon travel in a straight (green) line χ at the finite speed c with the 'disk' rotating underneath it. So, *relative to the surface of the disk*, the photon traces the curve r. However, what we see here as a curved red line is a perfectly straight line in space for the accelerated observer, for it is the geodesic path of light that is experienced by the ideally rotating observer *in the accelerated reference frame*.

When the 'disk' K' rotates, the green line, which is the coordinate radius, is not a path along which an observer rotating with the disk can make spatial interval measurements, because light cannot follow this path. The path of light follows the curve r, so this represents *space* in K' along which "the radius of the disk" can be measured by the accelerated observer. There are two distinct but related coordinate systems for K': the geometric reference coordinate system with radius χ, and the physical (spatial) coordinate system with radius r. Note that in relation to χ, the physical radius r dilates in exact proportion to the relativistic dilation of the circumference C'. Due to the rotation of K', the coordinate χ represents a varying abstract *mixture* of space *and* time from the point of view of the accelerated observer. One cannot assume that it is 'space', per se.

Another perspective



A difference between a space measurement and a time measurement produces a new space measurement. In other words, in the space measurements of one man there is mixed in a little bit of time, as seen by the other. …Now in [the Lorentz transformations and the Minkowski metric] nature is telling us that time and space are equivalent; time becomes space; they should be measured in the same units.
–Richard Feynman [1]

The scene of action of reality is ... a four-dimensional world in which space and time are linked together indissolubly. However deep the chasm that separates the intuitive nature of space from that of time in our experience, nothing of this qualitative difference enters into the objective world which physics endeavours to chrystalise out of direct experience. It is a four dimensional continuum, which is neither "space" nor "time".
–Hermann Weyl [2]

From the absoluteness of the speed of light, Einstein deduced by an elegant logical argument ... that if you and I move relative to each other, *what I call space must be a mixture of your space and your time, and what you call space must be a mixture of my space and my time.*
–Kip Thorne [3]

1. Richard Feynman, *The Feynman Lectures on Physics, Volume I*, (Addison-Wesley, Reading, Massachusetts, 1963), pp. 17-1 through 17-3.
2. J. J. O'Connor & E. F. Robertson, *MacTutor History of Mathematics archive*, St. Andrews University, Scotland, School of Mathematics and Statistics, "A history of time: 20th century time"; http://www-history.mcs.st-andrews.ac.uk/history/HistTopics/Time_2.html [recommended reading]
3. Kip Thorne, *Black Holes & Time Warps, Einstein's Outrageous Legacy*, (W.W. Norton, New York, 1994), p. 73.

Einstein’s mistake

- The ‘direction of the radius’ is the *curved* geodesic.
- This measured radius increases in proportion to the measured circumference, so ‘the surface of the disk’ remains Euclidean.
- The insight was brilliant, but general relativity was off track in 1909, even before Einstein began work on the field equations.

If the observer applies his standard measuring-rod (a rod which is short as compared to the radius of the disc) tangentially to the edge of the [rotating] disc, then, as judged from the Galileian system [inertial frame K], the length of this rod will be less than 1, since, according to Section 12, moving bodies suffer a shortening in the direction of the motion. On the other hand, the measuring-rod will not experience a shortening in length, as judged from K, if it is applied to the disc in the direction of the radius. If, then, the observer first measures the circumference of the disc with his measuring-rod and then the diameter of the disc, on dividing the one by the other, he will not obtain as quotient the familiar $\pi = 3.14\ldots$, but a larger number, whereas of course for a disc that is at rest with respect to K, this operation would yield π exactly. This proves that the propositions of Euclidean geometry cannot hold exactly on the rotating disc, nor in general in a gravitational field, at least if we attribute the length 1 to the rod in all positions and in every orientation.

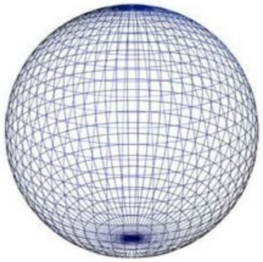
Albert Einstein, *Relativity, The Special and the General Theory*, 15th Edition, (Three Rivers Press, New York, 1952), p. 90.

‘Excess circumference’

The principles of relativity imply that an accelerated observer in a rotating frame of reference finds that the measured *physical* radius as well as the circumference corresponding to a fixed radial *coordinate* of the system increases in proportion to the acceleration experienced at that coordinate. Accordingly, the observer finds that the acceleration of the reference frame effectively increases the total spatial extent (*measured* square area) of the ‘disk’ defined by that fixed radial coordinate. In effect, the acceleration has geometrically ‘converted’ what is *measured* by an inertial observer to be time into the extra space *measured* by the accelerated observer.

The Einstein equivalence principle implies that the identical effect also occurs for a gravitational field created by mass, but in all three dimensions of the gravitational acceleration. Thus, the presence of mass-energy alters the surrounding spacetime geometry to create both the ‘excess radius’ of Einstein’s original theory and also an ‘excess circumference’ that was not modeled by the original theory. This implies observable empirical phenomena that are also not modeled by the original theory.

The physical circumference and surface area associated with a *coordinate* sphere increases as a function of the mass inside of it.



The Schwarzschild metric

For the practical engineering purposes of modeling relativistic effects of the gravitational field, which is of concern for such systems as precision celestial navigation software and the global positioning system (GPS), we may assume a spherically symmetric gravitating body, ignore rotation and consider only the static external solution. This is a close approximation to the pertinent features of a typical star or planet such as is found in our Solar System and in 1916 Karl Schwarzschild used just these simplifications to derive an exact solution to the Einstein field equations. [1]

Schwarzschild metric
'curved spacetime'

$$ds^2 = \left(1 - \frac{2M}{\chi}\right) d\tau^2 - \left(1 - \frac{2M}{\chi}\right)^{-1} d\chi^2 - \chi^2\left(d\theta^2 + \sin^2\theta\, d\phi^2\right)$$

gravitational redshift

excess radius

but no excess circumference

Minkowski metric
'flat spacetime'

$$ds^2 = d\tau^2 - d\chi^2 - \chi^2\left(d\theta^2 + \sin^2\theta\, d\phi^2\right)$$

The existence of an 'excess radius' is clearly prominent in the Schwarzschild metric. Equally prominent is that the dimensions transverse to the radius (θ, ϕ) have no corresponding coefficient, which is why the spacetime it describes is called 'curved'. It should be noted that in the weak field, where the characteristic gravitational escape velocity is much less than the speed of light, $2M \ll \chi$.

1. Karl Schwarzschild, "Über das Gravitationsfeld eines Massenpunktes nach der Einsteinschen Theorie", *Sitzungsberichte der Königlich Preußischen Akademie der Wissenschaften zu Berlin*, 189-196 (1916); Translation and Forward by S. Antoci & A. Loinger, arXiv: physics/9905030.

Schwarzschild assumptions

- A static and isotropic gravitational field in vacuum about a point-like mass.
- This is a very close approximation to the field around a typical star or planet.
- EEP implies that a Minkowski manifold rotating around its imaginary axis is the perfect theoretical inertial acceleration analog to such a field.

Escape velocity

- Energy conservation implies that the tangential velocity ($\omega\chi$) of an eccentric point of a rotating system of coordinates is the direct analog of the characteristic gravitational escape velocity.
- We are then entitled to substitute 'gravitational escape velocity' (v_{esc}) for the tangential velocity of a rotating point.

$$\int F \cdot d\chi = \int \frac{(\omega\chi)^2}{\chi} d\chi = \omega^2 \int \chi \cdot d\chi = \frac{1}{2}\omega^2\chi^2$$

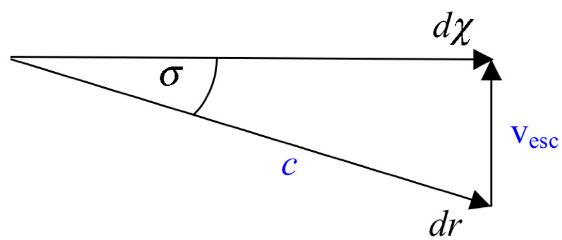
Time dilation

- An ideal clock (τ) of an inertial observer at the origin of a rotating frame.
- An accelerated clock (t) has tangential velocity v_{esc} relative to this clock.
- SR applies to the inertial clock, but not to the accelerated clock.

$$\frac{dt}{d\tau} = \sqrt{1 - \frac{v_{esc}^2}{c^2}} \qquad \frac{d\tau}{dt} = \frac{1}{\sqrt{1 - \frac{v_{esc}^2}{c^2}}}$$

Radius dilation

- Geometric relationships implied by the vector diagram for a neighborhood of a rotating point.



$$\sin\sigma = \frac{v_{esc}}{c} \qquad \cos\sigma = \frac{d\chi}{dr}$$

$$\rightarrow \frac{d\chi}{dr} = \sqrt{1-\sin^2\sigma} = \sqrt{1-\frac{v_{esc}^2}{c^2}}$$

Coordinate relationships

$$dr = \left(1 - \frac{v_{esc}^2}{c^2}\right)^{-\frac{1}{2}} d\chi \qquad dt = \left(1 - \frac{v_{esc}^2}{c^2}\right)^{\frac{1}{2}} d\tau$$

$$\int_{\infty}^{\chi} \frac{GM}{\chi^2} d\chi = \frac{1}{2} v_{\text{esc}}^2 \quad \rightarrow \quad v_{\text{esc}} = \sqrt{\frac{2GM}{\chi}}$$

$$dr = \left(1 - \frac{2GM}{\chi c^2}\right)^{-\frac{1}{2}} d\chi \qquad dt = \left(1 - \frac{2GM}{\chi c^2}\right)^{\frac{1}{2}} d\tau$$

$$G, c = 1 \quad \rightarrow \quad dr = \left(1 - \frac{2M}{\chi}\right)^{-\frac{1}{2}} d\chi \qquad dt = \left(1 - \frac{2M}{\chi}\right)^{\frac{1}{2}} d\tau$$

Note: Use a constant for 2M in Mathematica®.

$$r = \int \left(1 - \frac{2M}{\chi}\right)^{-\frac{1}{2}} d\chi = \sqrt{\chi^2 - 2M\chi} + 2M \ln\left(\sqrt{\chi - 2M} + \sqrt{\chi}\right)$$

The Minkowski metric

- According to first principles, all freefalling observers experience spacetime to be a *Euclidean* 3+1 manifold.

$$ds^2 = -dt^2 + dr^2 + r^2\left(d\theta^2 + \sin^2\theta d\phi^2\right)$$

However, observers at distinct locations in a gravitational field *interpret* coordinates differently. When we substitute the global reference coordinates from the previous slide into the above metric, this becomes apparent…

The corrected space-time metric

Retaining the essential form of the Schwarzschild metric with four space-time variables, the new metric is an oversimplification, for it does not express that for each point n over a circuitous route at fixed radius χ, there is a *unique* time coordinate t_n. However, symmetry and the relativistic spatial expansion of the route implies this fact.

Amended metric
'dilated spacetime'

$$ds^2 = \left(1 - \frac{2M}{\chi}\right) d\tau^2 - \left(1 - \frac{2M}{\chi}\right)^{-1} d\chi^2 - \Psi^2(\chi)\left(d\theta^2 + \sin^2\theta\, d\phi^2\right)$$

excess circumference

$$\Psi(\chi) = \sqrt{\chi^2 - 2M\chi} + 2M \ln\left[\sqrt{\chi - 2M} + \sqrt{\chi}\right]$$

For the surface of the Earth, $M \equiv \frac{GM_\oplus}{c^2} = \frac{6.673 \times 10^{-11} \cdot 5.9736 \times 10^{24}}{\left(2.998 \times 10^{8}\right)^2} = 4.435 \times 10^{-3}\, m$

$$\chi \approx R_\oplus = 6.671 \times 10^{6}\, m$$

$$\frac{\Psi^2(\chi) - \chi^2}{\chi^2} = 2.235 \times 10^{-8}$$

This implies that for the surface of the Earth, the only difference between the new metric and the conventional Schwarzschild metric is that the coefficient in the third term increases from unity by about 1 part in 45 million.

Bending of light

Einstein's successful prediction that a gravitational field would 'bend' light according to the following equation was one of the spectacular early empirical proofs of his theory. Modern techniques that confirm the prediction for the Sun of 1.75 seconds of arc have taken advantage of quasar radio frequency radiation, and Very Long Baseline Interferometry (VLBI) to reduce the experimental error to about 0.2% [1]

$$\alpha = \frac{4Gm}{bc^2} \equiv \frac{4M}{b} \qquad \alpha\left(M_\odot, b_\odot\right) = 8.487 \times 10^{-6} \approx 1.75''$$

Oddly enough, it is well-known that this equation is 'wrong' because while it is proven to be accurate in the weak field, it it yields an obviously meaningless result of 2 radians in the strong field limit, where the gravitational escape velocity approaches the speed of light. The correct equation must be a *general solution* that always correctly describes the empirical behavior of light in a gravitational field. As previously mentioned, the path of light is the null geodesic, so what we are looking for is the equation of a null geodesic described by the space-time metric for which the minimum radius or 'impact parameter' is b. It is trivial to determine that this must be a trajectory with an eccentricity of

$$e = \frac{b}{2M}$$

This immediately implies that the angle through which the trajectory 'bends' (the angle of intersection of the hyperbola's asymptotes) is

$$\alpha = 2\sin^{-1}\frac{2M}{b}$$

Because the sine of a small angle is equal to that angle, the arcsine function is redundant in the weak field, so the equation reduces to Einstein's formula, which it must, because empirical observation has confirmed its accuracy for the Sun. The question is, what happens as we approach the strong field limit, i.e., the vicinity of a black hole? A naïve but functional way to determine the relevant value of the impact parameter is to set the gravitational escape velocity equal to the speed of light, which gives us what is called the 'Schwarzschild radius'.

$$c = \sqrt{\frac{2Gm}{b}} \rightarrow b = \frac{2Gm}{c^2} \equiv 2M$$

$$e = \frac{2M}{2M} = 1 \qquad \alpha = 2\sin^{-1}\frac{2M}{2M} = \pi$$

The green line is curved relative to the straight purple line about 3,600 times *more* than the curvature of light near the surface of the Sun.

1. D. S. Robertson, W. E. Carter & W. H. Dillinger, "New measurement of solar gravitational deflection of radio signals using VLBI", *Nature* **349**, 768-770 (1991).

Continued…

Photon ‘celestial mechanics’

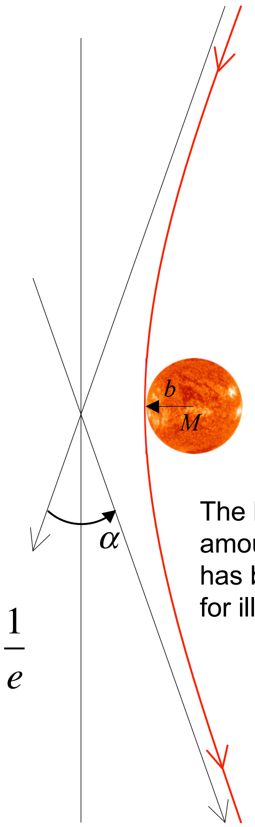
$$e = \frac{b}{2M} \qquad \alpha = 2\sin^{-1}\frac{2M}{b}$$

These equivalent equations, repeated from the previous slide, imply that as the local gravitational escape velocity approaches the speed of the photon (the speed of light c) the hyperbolic trajectory of the photon approaches a parabolic trajectory $(e = 1)$. This correlates with a fundamental law of celestial mechanics. The law states that in a dominant symmetric gravitational field, the orbit of a ‘test particle’ will be a conic section; specifically, when the velocity of the particle is greater than the escape velocity of the the field, the trajectory will be hyperbolic and when the velocity of the particle is equal to the escape velocity, the trajectory will be parabolic. Because this fundamental geometric physical law is mass-independent, it is not surprising that it should apply to photons, which carry energy and momentum through space but have zero mass.

The angle at which the asymptotes of a hyperbola intersect represents the angle through which an associated trajectory ‘bends’. The eccentricity of the null geodesic in the weak field is a large number, so the deviation of the hyperbolic trajectory from a straight line is very small but not zero. For a photon from a distant star or quasar that grazes the surface of the Sun, the eccentricity of the trajectory is about $e = 2.36\times10^5$.

$$\sin\frac{\alpha}{2} = \frac{1}{e}$$

$$\rightarrow \alpha = 2\sin^{-1}\frac{1}{e}$$



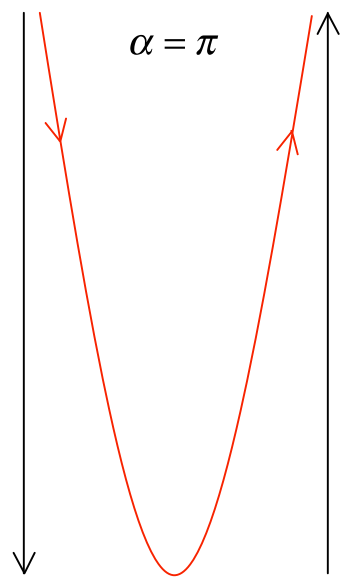
The bending of light by the Sun, which amounts to about 1/2000th of a degree has been enormously exaggerated here for illustrative purposes.

hyperbolic trajectory

$e > 1$

The angle through which a trajectory with an eccentricity of $e = 1$ effectively ‘bends’ is π radians.

$$\alpha = \pi$$



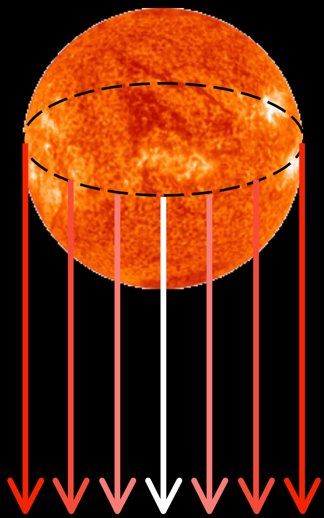
parabolic trajectory

$e = 1$

Empirical evidence

- Theoretical physics is a meaningless exercise without predictions that can be empirically verified.
- The following slides discuss several distinct observations that demonstrate the existence of the *GTR* effect…

Excess redshift of stars



Note that *GTR* implies an *apparent* Doppler velocity asymmetry favoring redshift over blueshift that may be observable for the respective sides of the solar equator.

From the point of view of a distant observer, the majority of a star's photons are emitted from a region that is off-center, so their path will have a component transverse to the star's radial gravitational gradient. It follows that *GTR*, superimposed on the modeled Einstein gravitational redshift, will cause an anomalous redshift to occur for photons that are sourced from various points along the radius of the star with no anomalous effect observed at the center point and the maximum anomalous effect occurring at the limb. With the exception of the Sun, observations of starlight cannot make this geometric distinction of a radial differential, so the effect will generally manifest as an unmodeled redshift of starlight.

Brighter Class B stars (larger stars such as Rigel in Orion) typically exhibited an apparent excess redshift of $K \approx +4\ km/s$. Interpreted as a Doppler shift, the K-Effect makes the inference that larger, hotter stars have the implausible quality of a systematically higher recession velocity relative to the Sun than smaller, cooler stars.

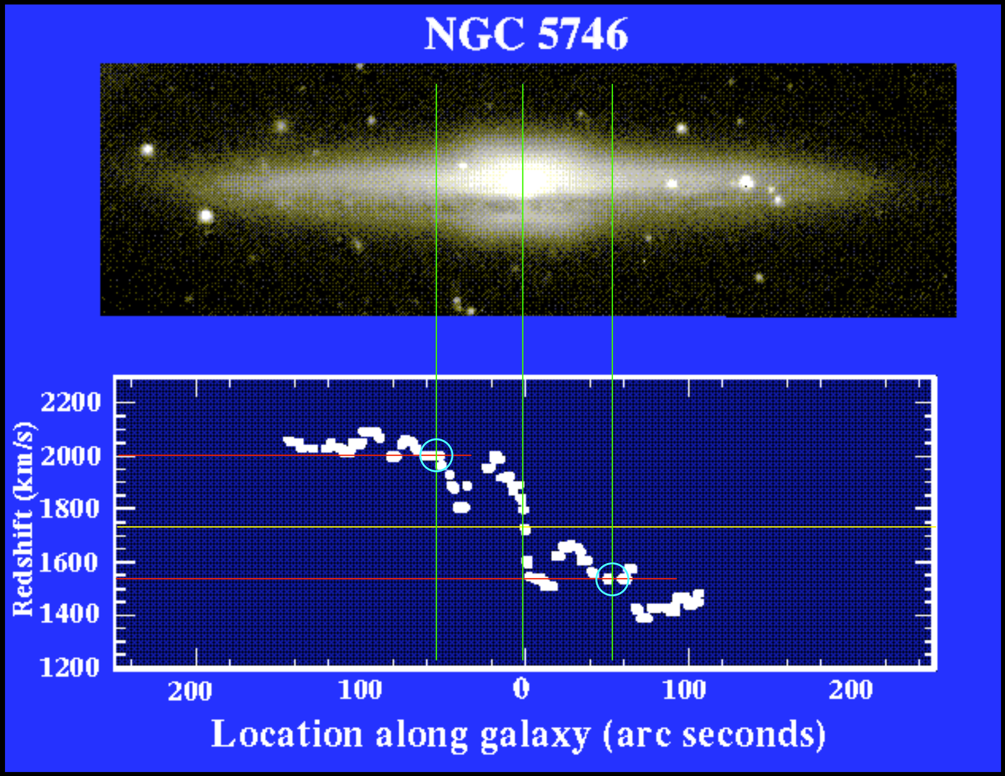
Due to their very significantly increased density and commensurately far stronger surface gravitational field as compared to main sequence stars, this phenomenon of a radial redshift differential with maxima occurring at the limb is particularly pronounced for white dwarf stars. The observed excess redshift in the range of 10-15 km/s cannot be misinterpreted as an Einstein gravitational redshift because it has been recognized that the relativistic mass associated with this interpretation of the observed redshift implies a mass that is far too large for such a star according to astrophysical considerations.

It is remarkable that the "relativistic" masses of the white dwarf stars, which one obtains by reduction of the observed redshifts, are (on the average, with large scatter) significantly larger than the "astrophysical" ones… Various attempts to explain this discrepancy have been made in the past, e.g., by asymmetry-induced shifts due to slope of the continuum (Schulz 1977) but this problem still is not solved (see also the review by Weidemann 1979). In velocity units the systematic excess of the observed redshift amounts to 10–15 $km\ s^{-1}$ (Shipman and Sass 1980; Shipman 1986) above "residual" redshift (i.e., redshift free of all kinematic effects).

B. Grabowski, J. Madej, & J. Halenka, "The Impact of the Pressure Shift of Hydrogen Lines on 'relativistic' Masses of White Dwarfs", *Astrophysical Journal* **313**, 750-756 (1987).

Galaxy rotation curve asymmetry

Spiral galaxy rotation curves exhibit a known but unexplained asymmetry. Due to the gravitating mass of the galaxy, *GTR* must cause an unmodeled increase in the redshift and a decrease in the blueshift, causing an asymmetry in the two distinct curves. Thus, *it must always be the blueshift that is observed to be asymmetrically less than the redshift*. It is then obvious that a mass-dependent phenomenon that causes a general redshift is superimposed on what must be a very nearly radially symmetric relative velocity Doppler shift due to the circular rotation. None of the existing literature on the subject of observed rotation curve asymmetry seems to have picked up on this observational detail. *GTR* implies that, with the rare exception of obvious external influences, it will never be the blueshift side that is observed to exhibit an apparent Doppler shift that on average has a greater magnitude than the apparent Doppler shift on the redshift side. This observation, alone, is a *definitive* empirical confirmation of the *GTR* effect.



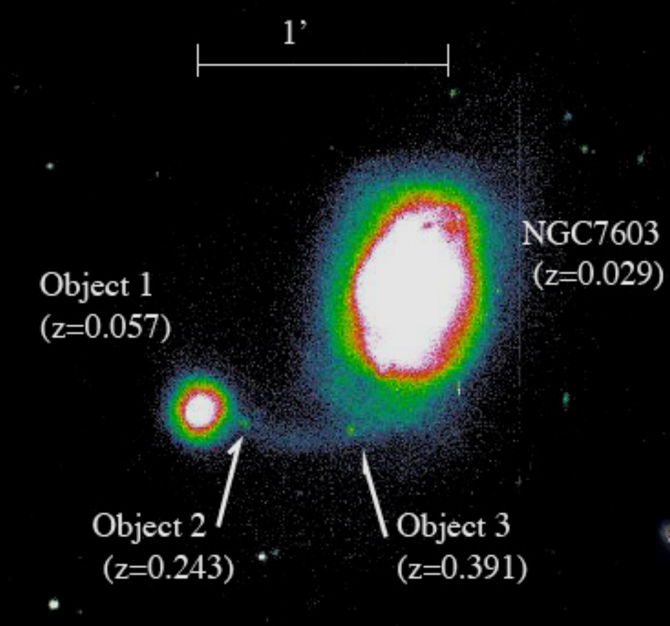
It is clear from this rotation curve of NGC 5746, that the right side is approaching while the left side is receding. The velocity asymmetry for the region just exterior to the bulge where the mass concentration is greatest is evident, with the observed blueshift being substantially less than the redshift. This observation is predicted to be a ubiquitous feature of spiral galaxies, indicating that a component of the measured redshift of galaxies is caused by the *GTR* effect. On a galactic scale, this is the identical effect that has been seen in the form of the solar radial redshift differential and is predicted to be observed as a solar spin Doppler asymmetry.

The image is a red-light CCD frame taken by William C. Keel, University of Alabama, at the 42-inch Hall telescope of Lowell Observatory. The rotation curve was measured using the GoldCam CCD spectrometer at the 84-inch telescope of Kitt Peak National Observatory. Reproduced with permission.

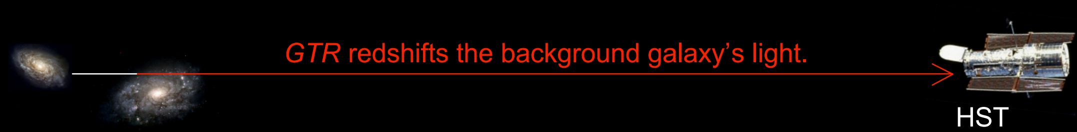
Anomalous redshift of background galaxies

We present new observations of the field surrounding the Seyfert galaxy NGC 7603, where four galaxies with different redshifts – NGC 7603 (z = 0.029), NGC 7603B (z = 0.057) and two fainter emission line galaxies (z = 0.245 and z = 0.394) – are apparently connected by a narrow filament, leading to a possible case of anomalous redshift. The observations comprise broad and narrow band imaging and intermediate resolution spectroscopy of some of the objects in the field. The new data confirm the redshift of the two emission-line objects found within the filament connecting NGC 7603 and NGC 7603B, and settles their type with better accuracy. Although both objects are point-like in ground based images, using HST archive images we show that the objects have structure with a FWHM = 0.3-0.4 arcsec. … The probability of three background galaxies of any type with apparent B-magnitudes up to 16.6, 21.1 and 22.1 (the observed magnitudes, extinction correction included) being randomly projected on the filament of the fourth galaxy (NGC 7603) is ~3×10^{-9}. Furthermore, the possible detection of very vigorous star formation observed in the HII galaxies of the filament would have a low probability if they were background normal-giant galaxies; instead, the intensity of the lines is typical of dwarf HII galaxies. Hence, a set of coincidences with a very low probability would be necessary to explain this as a fortuitous projection of background sources

M. López-Corredoira & Carlos M. Gutiérrez, "The field surrounding NGC 7603: Cosmological or non-cosmological redshifts?", *Astronomy & Astrophysics* **421**, 407-423 (2004); arXiv: astro-ph/0401147.



It should now be clear that what is being observed here and what has been observed for many years in pioneering observations by Halton Arp is the galactic *GTR* effect. Background light passing transverse to the galactic gravitational field is redshifted, so objects that may in fact be in close proximity to one another in physical space may have distinctly different measured redshifts. Object 3 exhibits the largest anomaly as its light path is immediately adjacent to NGC 7603. Object 2 is next as its light skirts Object 1. Object 1 has the smallest anomalous redshift as there is significant radial separation from NGC 7603.



Differential redshift of lensed quasars

The double quasar *Q* 0957+561, discovered in 1979, was the first identification of gravitational lensing of a distant quasar. A number of other examples, such as the famous quadruple-image Einstein Cross, *Q* 2237+0305 have been identified since then. The phenomenon occurs when a massive object, typically a galaxy or cluster of galaxies is in the line of sight to the distant quasar. Two or more images of the identical astronomical object are observed due to alternate paths taken by the light. A lensed photon, which takes a longer path from source to observer than a direct photon, will be subject to a time-delay. When multiple images of a lensed object are observed, only a relative time-delay can be observed, since the unlensed source is never visible, having been obscured by the intervening lensing object. Characteristic photometric variations in the source quasar allow for definitive matching of distinct light curves to determine which observed image took a longer time to arrive and thus pursued a longer path from source to observer.

Conventional wisdom would have it that a photon that descends and subsequently reemerges from a gravitational well will suffer no net energy loss. However, the *GTR* effect implies that transverse travel through a gravitational field must cause a net loss in energy. It follows that rather than exhibiting identical spectrums, multiple images of lensed quasars will exhibit slightly differential redshift; it is predicted that a greater redshift will always be observed for light that pursues the more indirect path, suffering more significant gravitational interaction and thus arriving later.

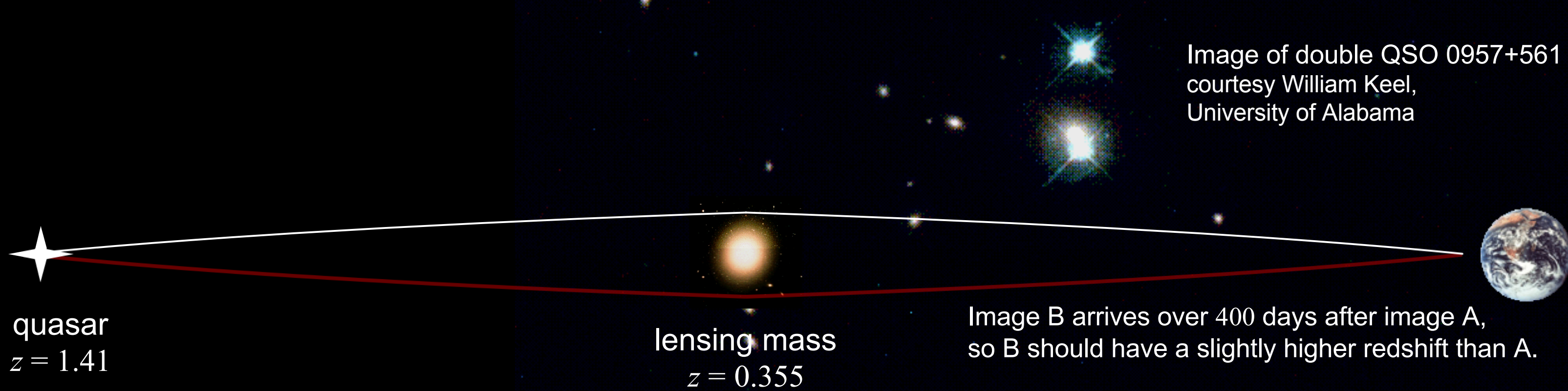


Image of double QSO 0957+561
courtesy William Keel,
University of Alabama

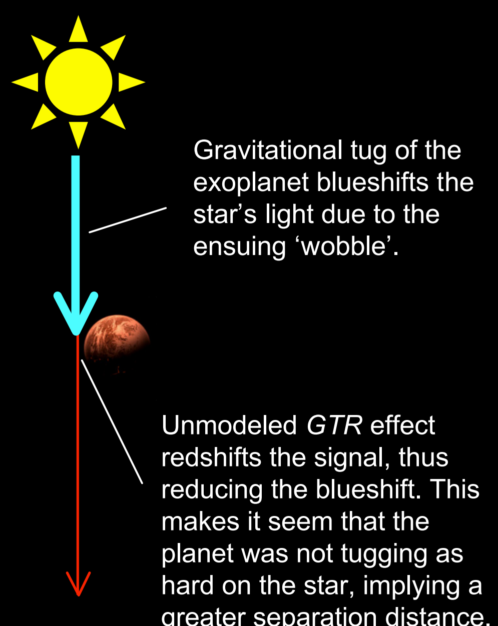
Image B arrives over 400 days after image A, so B should have a slightly higher redshift than A.

Alejandro Oscoz *et al.* "Time Delay of QSO 09571561 and Cosmological Implications", *Astrophysical Journal* **479**, L89–L92 (1997).

Dennis Walsh, Robert Carswell & Ray Weymann, "0957 + 561 A, B - Twin quasistellar objects or gravitational lens", *Nature*, **279**, 381 (1979).

Evidence from extrasolar planets

In 1995 Mayor and Queloz announced the discovery of the first extrasolar planet orbiting a main sequence star, a Jupiter-mass companion to the star 51 Pegasi inferred to exist from observations of periodic variations in the star’s radial velocity determined by Doppler-shift measurement. Many other such extrasolar planets have been found using the identical Doppler-shift method. A second successful method that has initially been used more recently (2003) is the transit method, whereby the apparent brightness of a star is perturbed by a large orbiting planet passing in front of it along the line of sight. The unmodeled *GTR* effect causes the two techniques to provide different results. The actual blueshift of the star due to the gravitational tug of the planet is reduced due to the *GTR* effect. Because the GTR effect is unmodeled, the interpretation of the Doppler data is that the planet is farther away from the star than is actually the case, implying a longer orbital period. On the other hand, the transit technique precisely times the orbital period based on the period of occultation.



It is not clear how these planets could get so close to their star…

The Doppler technique is most sensitive to planets in close orbit around their stars, but no orbital periods shorter than about 2.5 days have been found with this technique.

[Using the transit method] the candidate planet is quite surprising, with an orbital period of 1.2 days. This is half the shortest period for a planet found using the Doppler-shift method.

What is disturbing is that no ‘hot Jupiters’ [period ≥ 2.5d] were found in the transit survey, and no Doppler survey has found a ‘very hot Jupiter’ [period ~1d].

We are left with an interesting mystery, which will require more observations and analysis to resolve. Either a new and insidious sort of false-positive for transit surveys has been found, or our theories of planetary systems need to be further expanded. In either case, the sensitivity of these surveys clearly needs to be better understood.

Gibor Basri, “Too close for comfort”, *Nature* **430**, 24 (2004).

The Blackdrop Effect

Earth is the third planet from the Sun after Mercury and Venus. Therefore, on occasion and from the right location on Earth, these two inner planets can be observed to transit the solar disk, appearing as a dark round shadow moving across the background of the Sun. Observations of these events have been marked by a peculiar phenomenon which became commonly known as the 'Black Drop' effect. This is an observed meniscus between the respective limbs of the Sun and Venus that distorts the anticipated sharp circular outline of the planet when its limb is internally tangent to that of the Sun at both ingress (Contact II) and egress (Contact III). This distortion of the background light streaming past the planet's limb made it frustratingly impossible to accurately time the moments that the transit began and when it ended. Historically, a number of possible explanations were posited for this puzzling observation. These included a simple optical illusion, light diffraction around the planetary disk, refraction by the atmosphere of Venus, or terrestrial atmospheric 'seeing' effects whereby the Earth's atmosphere smears the light, which is typically the case for telescopic observations of stars. Photographic images revealed the effect, so it was clearly not an optical illusion and the calculated magnitude of possible diffraction effects is entirely negligible. Throughout the 20th century, it seemed inevitable then that one or both of the other two remaining purported causes was correct. However, in both 1999 and 2003, the NASA Transition Region and Coronal Explorer (TRACE) spacecraft was used to make high spatial resolution optical images of the transit of Mercury. The effect was clearly observed by the spacecraft cameras, eliminating the possibility of either of these explanations. Due to the gravitational transverse redshift effect, the background sunlight streaming past the transiting planet will incur a radial redshift differential with a pronounced redshift at the limb. This will clearly cause an asymmetric line broadening, a phenomenon which can be easily verified during observations of the November 2006 transit of Mercury and the June 2012 transit of Venus, and perhaps even from archive data from the previous transits. It is virtually certain that what we are looking at in this TRACE image of the 2004 Venus transit, and what has been similarly been seen for centuries, is direct evidence of *GTR*.

Venus transit on 8 June 2004 observed by TRACE

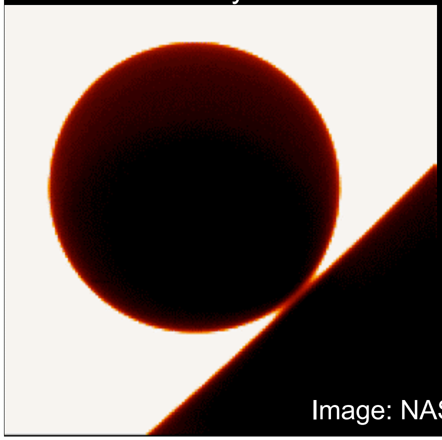


Image: NASA

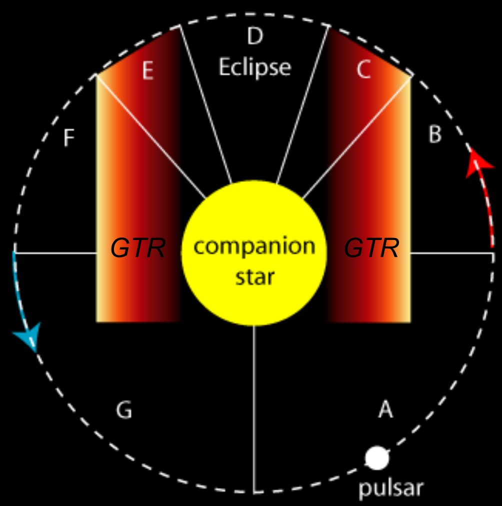
The principal cause of the Black Drop effect, which has historically impeded ground-based planetary transit measurements, is *optical broadening* resulting from the convolution of the systemic PSF [Point Spread Function] with the planetary and limb-darkened solar disks. TRACE observations are free from PSF instabilities caused by "seeing" in the terrestrial atmosphere and allow mitigation of the Black Drop effect from the intrinsic disk images. Such stable, critically sampled, near diffraction-limited images may be further enhanced by PSF deconvolution, enabling very high-precision differential astrometric position measures.

Glenn Schneider, Jay M. Pasachoff and Leon Golub, "TRACE observations of the 15 November 1999 transit of Mercury and the Black Drop effect: considerations for the 2004 transit of Venus", *Icarus* **168**, 249-256 (2004).

Eclipsing binary stars

Due to their strong gravitational field, eclipsing binary stars are ideal astrophysical laboratories for the study of the *GTR* effect and systems that include a radio pulsar are particularly advantageous. Only some 3% of known pulsars are members of binary systems with a special subclass of these being eclipsing systems due to fortuitous orbital configuration of the two stars in relation to the Sun. The figure here is a simple schematic diagram depicting various distinct regions in the ephemeris of a binary eclipsing pulsar with the 6 o'clock position representing the line-of-sight to an observer on Earth. Rather than showing an accurate ephemeris relative to the barycenter (the system center of mass) the intent is only to show the relative geometric configurations of the two stars relative to the observer during distinct phases in the orbit. The pulsar's motion is counterclockwise.

At inferior conjunction, when the pulsar is 180° out of phase with the midpoint of eclipse, no *GTR* is in effect; the intrinsic pulsar frequency is observed. As the pulsar approaches eclipse, the unmodeled *GTR* effect increasingly superimposes an anomalous redshift on the modeled behavior in region B. The effect is highly non-linear with a very sharp spike occurring in region C, just prior to immersion, and also in region E, just after emersion. After emersion, the pulsar signal is observed to be unperturbed by *GTR* only at some point in region F, when the signal path is sufficiently distant from the limb of the companion. For particularly tight orbits, this may not occur until some point in region G. With the *GTR* effect having been unmodeled, it is generally the case that Doppler observations of binary systems will have suggested unlikely properties and ephemerides. The observation described below is entirely consistent with the predicted observable of the *GTR* effect, while the attempt at explanation by the authors is logically weak. How does a star with a tiny mass *eclipse* a speeding pulsar with a 9.17-hour period for 50 minutes (~33° of orbit)?



A remarkable pulsar with period 1.6 ms, moving in a nearly circular 9.17 hr orbit around a low-mass companion star, has been discovered. At an observing frequency of 430 MHz, the pulsar, PSR1957+20, is eclipsed once each orbit for about 50 minutes. For a few minutes before an eclipse becomes complete, and for more than 20 minutes after the signal reappears, the pulses are delayed by as much as several hundred microseconds – presumably as a result of propagation through plasma surrounding the companion. The pulsar's orbit about the system barycenter has a radius of 0.089 light seconds projected onto the line of sight. The observed orbital period and size, together with the fact that eclipses occur, imply a surprisingly low companion mass, only a few percent of the mass of the sun.

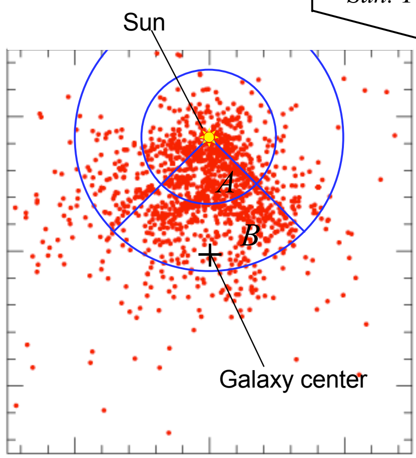
A. S. Fruchter, D. R. Stinebring & J. H. Taylor, "A millisecond pulsar in an eclipsing binary", *Nature* **333**, 237-239 (1988).

Pulsar population statistics

The first radio pulsar signal was discovered by Cambridge University graduate student Susan Jocelyn Bell in 1968. Pulsars are weak radio sources typically measured at ~400 MHz that are associated with a synchrotron radiation beaming phenomenon of rapidly rotating neutron stars. Pulsars classified as 'normal' have a pulse period on the order of 1 second but there also exists a class of so-called 'millisecond pulsars' with measured pulse frequencies that may be in excess of 600 Hz; the overwhelming majority of these are found in binary systems.

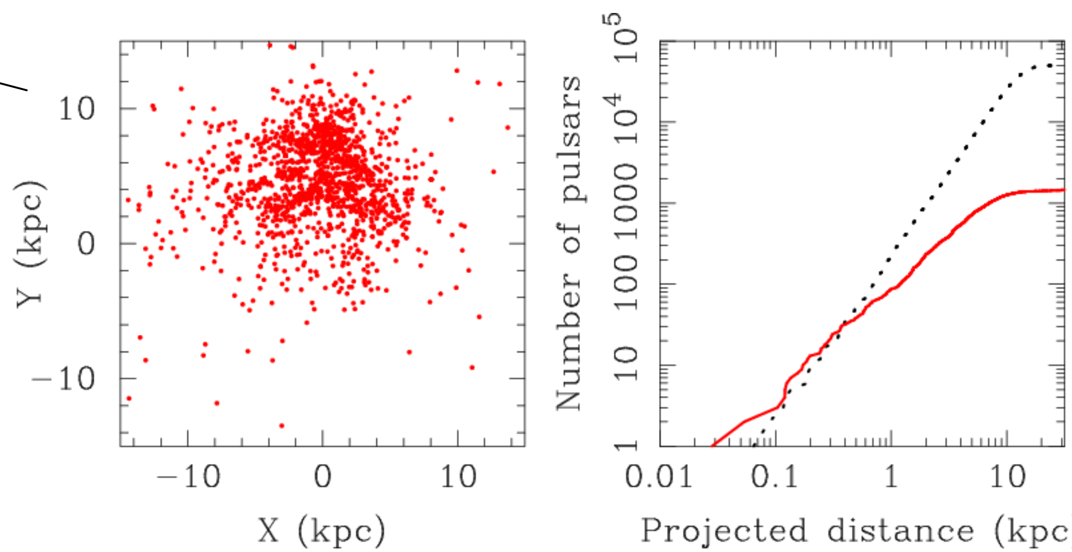
While individual pulsar properties vary widely, it is predicted that a more distant population of pulsars should exhibit the *frequency-independent* effects of a relativistic time dilation due to the *GTR* effect caused by the intervening mass of the galaxy. That is, a population of more distant pulsars (B) should exhibit statistically averaged slower pulse rates than a nearby population (A). Also, there should be a corresponding redshift in the broadcast spectrum. The galactic bulge will induce a large 'step function' GTR effect, so pulsars beyond the bulge will tend to have quite different observational properties than those on the Sun's side of the bulge. Radio astronomy software designed to find the latter will almost certainly filter out most of the former. The reason why the number of pulsars found in modern surveys at a distance greater than about 10 *kpc* (~33,000 *ly*) is noted to be at least an order of magnitude *less* than the expected distribution based on the nearby population is almost certainly because selection criteria will not have previously accounted for the galactic *GTR* effect.

Figure 11: *Left panel: The current sample of all known radio pulsars projected onto the Galactic plane. The Galactic centre is at the origin and the Sun is at* (0, 8.5) *kpc. Note the spiral-arm structure seen in the distribution which is now required by the electron density model [73, 74]. Right panel: Cumulative number of pulsars as a function of projected distance from the Sun. The solid line shows the observed sample while the dotted line shows a model population free from selection effects.*



Annotation of Lorimer's graph by A. Mayer.

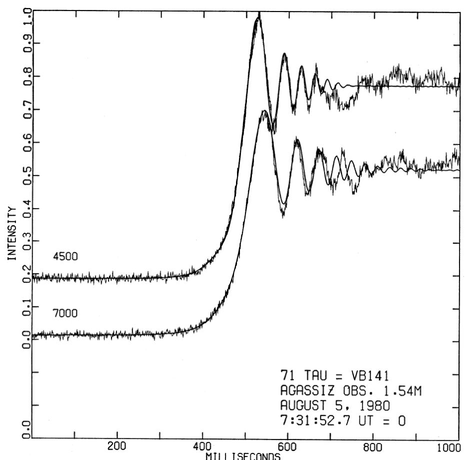
The *average* perceived pulse rate and also the radio frequency of the pulsar *population* in region B is predicted to be less than in A. The mass of the intervening disk produces a *GTR* time dilation effect on more distant pulsars. The central bulge has a much larger effect.



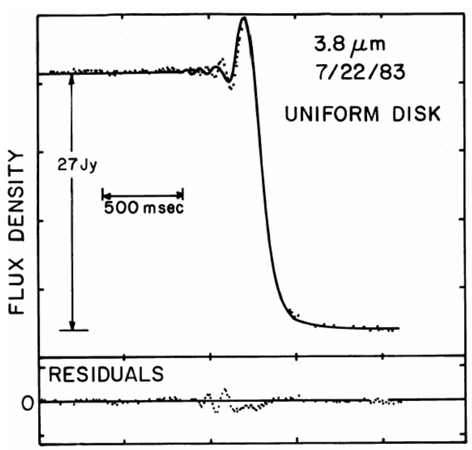
Duncan R. Lorimer, "Binary and Millisecond Pulsars at the New Millennium" ,
(Living Reviews in Relativity, Max-Planck-Institut für Gravitationphysik, Potsdam, 2005);
http://relativity.livingreviews.org/Articles/lrr-2005-7/

Lunar occultations

Light from a point source such as a distant star that is occulted by the Moon exhibits Fresnel diffraction with the shape of the diffraction curve being dependent on the apparent angular size of the stellar disk and the wavelength of the light being observed. The *GTR* effect implies that just prior to occultation (immersion) photons will exhibit an unmodeled redshift and just after emerging from lunar occultation, the initially observed unmodeled excess photon redshift will blueshift back to the intrinsic wavelength of the stellar source. Existing observations of lunar occultations are indeed accompanied by unmodeled behavior that defies definitive conventional description.



[Ref. 2]



[Ref. 3]

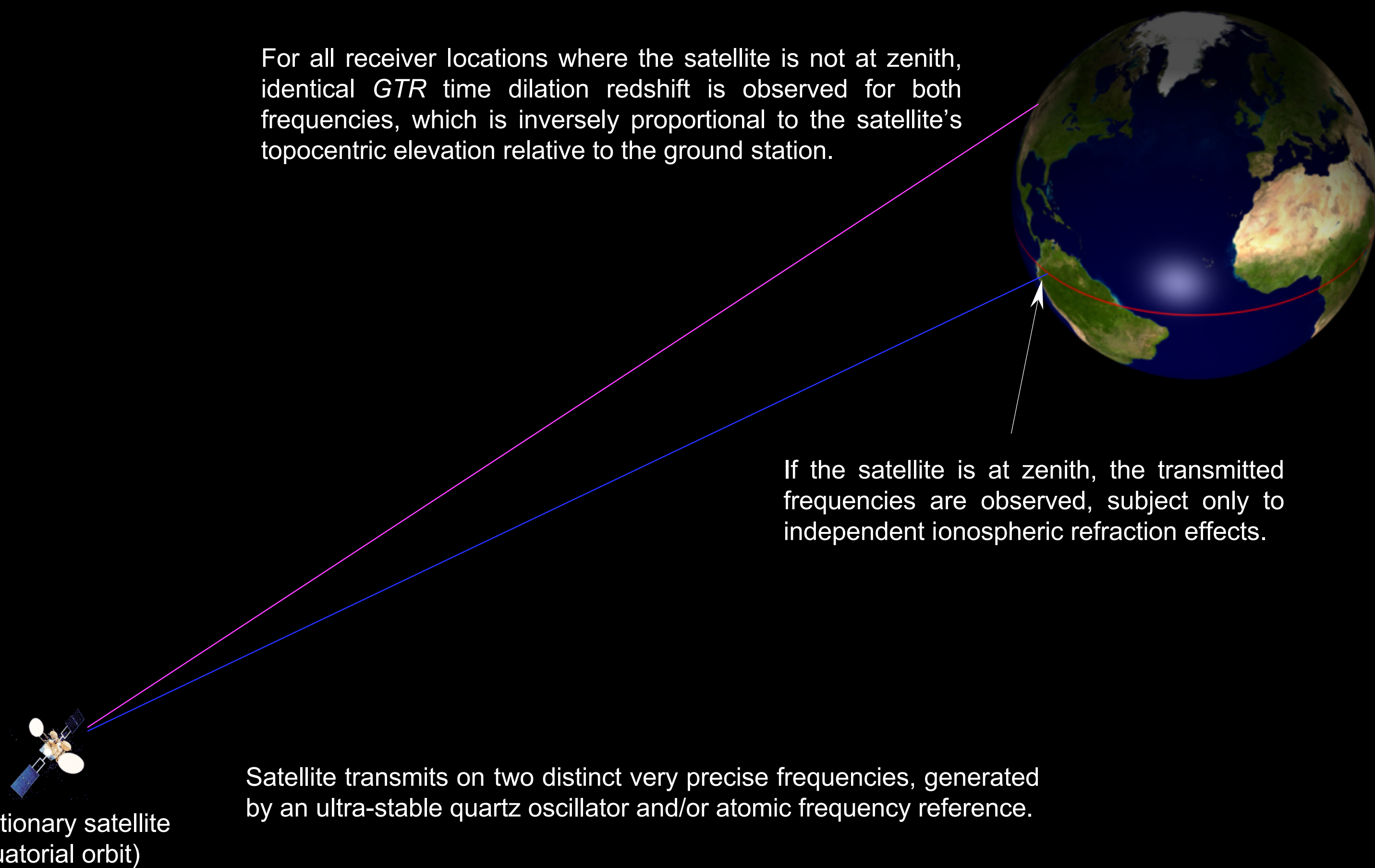
The top graph is data from an emersion event described below by Peterson *et al.* The observed marked deviation from modeled behavior (smooth solid line) occurs for wavelengths (filters) of 4500 and 7000 angstroms respectively. The unmodeled residuals from the immersion event in the lower graph by Michal Simon *et al.* also show a marked deviation from modeled behavior but at a wavelength (3.8 μm) which is an order of magnitude greater than that observed by Peterson's team. Note the difference in the graphs' time scales. These are just two of the best and clearest examples among others demonstrating that lunar occultations are characterized by an unmodeled change in the wavelength of radiation that is localized in the vicinity immediately adjacent to the lunar limb. These distinct observations demonstrate the identical unmodeled anomaly, so together they imply that that the observable is empirical, but not due to a physical obstruction or an experimental error.

> The most frustrating aspect of these data are the bad points in the red Agassiz channel. It is this channel in particular with its potentially high signal-to-noise ratio that should have provided the definitive detection. To have three glitches at just that point in the data record was extremely unfortunate. [1]
>
> Even here, the detection is not without some complications. …there is a strong distortion in the fringe pattern some 250 ms after the geometrical reappearance of the primary. We suggest that this is due to a limb distortion, since scintillation will produce deviations from the predicted signal, such as seen later in the tracings, that are strongly correlated in different wavelengths. … A boulder 10-20 m high could cause such a distortion. Note, particularly in the red channel, that the original fringe rate is recovered 50 ms further on. [2]

1. Deane M. Peterson *et al.*, "Lunar Occultations of the Hyades: 1979-1980", *Astronomical Journal* **86**, 280-289 (1981).
2. Deane M. Peterson, R. L. Baron, E. Dunham & D. Mink, "Lunar Occultations of the Hyades. II. August 1980", *Astronomical Journal* **86**, 1090-1097 (1981).
3. Michal Simon *et. al.*, "Lunar Occultation Observations of M8E-IR", *Astrophysical Journal* **298**, 328-339 (1985).

A simple experiment

Assuming a very precisely known and stable transmission frequency, *GTR* may be observed as a subtle geographically dependent variation in the received downlink frequency of a geostationary satellite that cannot be attributed to other phenomena. The effect will exhibit increasing anomalous redshift as the distance of the receiver from the satellite's equatorial longitude increases and the topocentric angle of the receiving station antenna is correspondingly depressed towards the horizon. The effect is significant as concerns the synchronization of atomic clocks using TWSTT (Two-Way Satellite Time Transfer).



TRANSIT

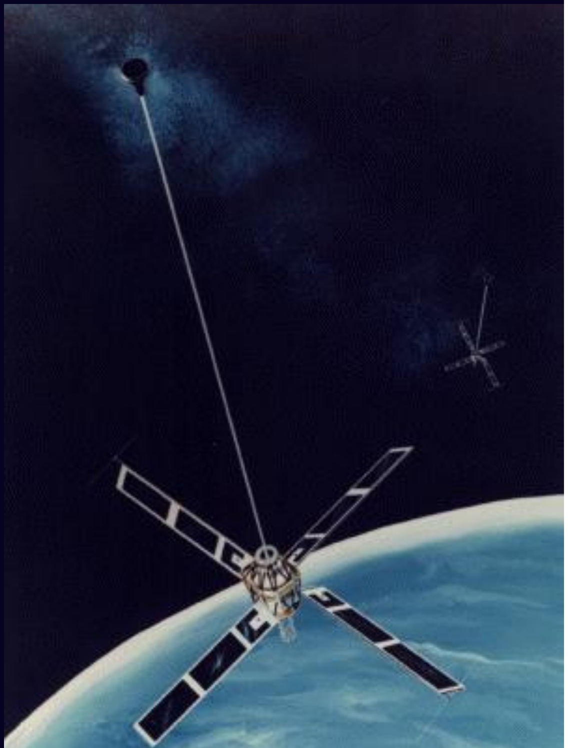
Satellite geodesy has its beginnings in a 1955 proposal by the U.S. Naval Research Laboratory authored by Martin Hotine, first director of the Britain's Directorate of Overseas Surveys, established after World War II and author of *Mathematical Geodesy*, published in 1969 by the U.S. Environmental Science Services Administration. Early space-based photographic processes gave way to the Navy Navigation Satellite System (NAVSAT) called TRANSIT, which evolved from an original constellation of five operational OSCAR satellites providing navigational service into three operational NOVA-2 satellites in low ($\sim 1{,}175\ km$) polar orbit with orbital periods of 109 minutes. The first successful tests of the system were conducted in 1960 and the system was continuously upgraded through the last satellite launch in June 1988. TRANSIT was retired in 1996, having been replaced by the NAVSTAR Global Positioning System. The primary mission of TRANSIT was to obtain accurate coordinates to support ballistic missile submarines, although it was also used more generally for navigation and surveying. The TRANSIT satellites broadcast a continuous dual-frequency signal ($150\ MHz$ and $400\ MHz$ in order to calculate ionospheric delays) with a 2-minute period that included the time and ephemeris. The system employed the Doppler effect, whereby the apparent dynamic frequency shift of a satellite signal combined with knowledge of its location at transmission yielded a 2-dimesional latitude/longitude fix for the location of the receiver; no altitude measurements were possible. The gravitational transverse redshift effect will have had a considerable unmodeled influence on the Doppler signals from the TRANSIT satellites, seriously degrading their expected performance. Estimates of TRANSIT's accuracy will have been erroneous, implying far more accurate coordinate values than was actually the case. The *GTR* effect will have been particularly insidious in introducing errors because it is dependent on the variable relative elevation of the satellite at transit.

The preliminary WGS 84 coordinates of the USAF and DMA [Defense Mapping Agency] GPS tracking stations were obtained by transformation from their WGS 72 coordinates. During 1985 and 1986, the WGS 84 coordinates were directly derived using Doppler TRANSIT point positioning by DMA. This positioning technique used the recently calibrated WGS 84 Doppler station coordinates, Doppler observations collected from TRANSIT satellites, and the WGS 84 gravity model. The WGS 84 positions of the GPS tracking stations were defined by transferring WGS 84 positions of nearby collocated Doppler stations using terrestrial survey differences.

…

Uncertainties in these Doppler-derived WGS 84 station coordinates were attributed principally to uncompensated ionospheric effects on signal propagation and, to a smaller extent, the determination of the electrical phase center of the antennas. TRANSIT, like GPS, used dual-frequency observations to correct for ionospheric effects. This correction's residual errors are inversely proportional to the satellite transmitted frequencies. Ionospheric corrections for the TRANSIT low-frequency observations contained relatively large residual errors; these errors primarily corrupted the height of Doppler-derived coordinates. Smaller errors in the GPS station coordinates were introduced by inaccurate definitions of the electrical phase center of both the TRANSIT and GPS antennas used in the coordinate transfers. The combination of these and other errors made the initial GPS station coordinates internally inconsistent and biased with respect to the BTS [Bureau International de l'Heure Terrestrial System]. The largest bias, which was in the GPS station heights, was estimated to be at the meter level. Over time, the BTS has been refined to the International Terrestrial Reference Frame (ITRF) provided by the International Earth Rotation and Reference Systems Service (IERS).

Alan G. Evans *et al*., "The Global Positioning System Geodesy Odyssey",
Navigation, Journal of the Institute of Navigation, **49**, (2002), pp. 8 & 11-12.



TRANSIT satellites, the precursor to GPS

Incorrect GPS altitudes

In addition to the Master Control Station (MCS), which is a part of Schriever Air Force Base just outside of Colorado Springs in the United States, there are four remote unmanned GPS Operation Control Segment Monitoring Stations (MS) worldwide that send raw pseudo-range data back to the MCS. From East to West these are: Hawaii, Kwajelein, Diego Garcia and Ascension. Because these stations collect ranging data and timing from each GPS constellation satellite and transmit this information back to the MCS, it is imperative that their geographic locations are precisely known. The accuracy of each station coordinate component is currently estimated to be on the order of 1 *cm*, 1 sigma.

Diego Garcia is on an island atoll that is part of the Chagos Archipelago in the British Indian Ocean Territory just south of the Equator at about 72º 22' E, 7º 16' S. As is common to virtually all such island atolls, the terrain has an average elevation of about 1-2 meters above local sea level and a maximum elevation not exceeding 10 meters. Kwajalein is a very similar island atoll that is part of the Marshall Island Group in the North Pacific Ocean, about half way between Hawaii and Australia just north of the Equator at about 167º 43' E, 8º 43' N. Malé Airport is about 1,280 *km* north of Diego Garcia in the Indian Ocean. Note the GPS heights of each of the islands shown on the left.

Earth's Geoid is defined by the U.S. National Geodetic Survey as "The equipotential surface of the Earth's gravity field which best fits, in a least squares sense, global mean sea level." Then the Geoid is that smooth surface that closely approximates the mean sea surface and is everywhere perpendicular to a local plumb line defining the direction of the local gravitational gradient. GPS measures elevation not relative to the Geoid, per se, but relative to a theoretical equipotential ellipsoid of revolution specified by the World Geodetic System 1984 (WGS 84) which was designed for use as the reference system for GPS. The relationship between the height H of the topographic surface of the Earth above the Geoid, the Ellipsoid height h that is specified by GPS and the Geoid height N relative to the ellipsoid is $h = H + N$. At mean sea level, by definition the value of H is zero, so here the ellipsoid height reported by GPS is then equal to the Geoid height relative to the ellipsoid, which at sea level should also be close to zero. The parameters of the reference ellipsoid, the semimajor axis a and the flattening f have been chosen so that the ellipsoid might very closely follow the Geoid. The Geoid height N or "undulation of the Geoid" relative to the ellipsoid should represent to good approximation the effects of gravitational anomalies due to density variations in the Earth's interior.

Then, from a geodetic and geophysical perspective, the GPS elevations of these three islands simply do not make sense. They are just as troubling as the Pioneer spacecraft's purported anomalous acceleration. Are we to believe that "a Geoid which undulates wildly across the landscape" reflects empirical reality? [1] We are not. The altitude anomalies are a reflection of GPS positioning errors introduced by the unmodeled *GTR* effect.

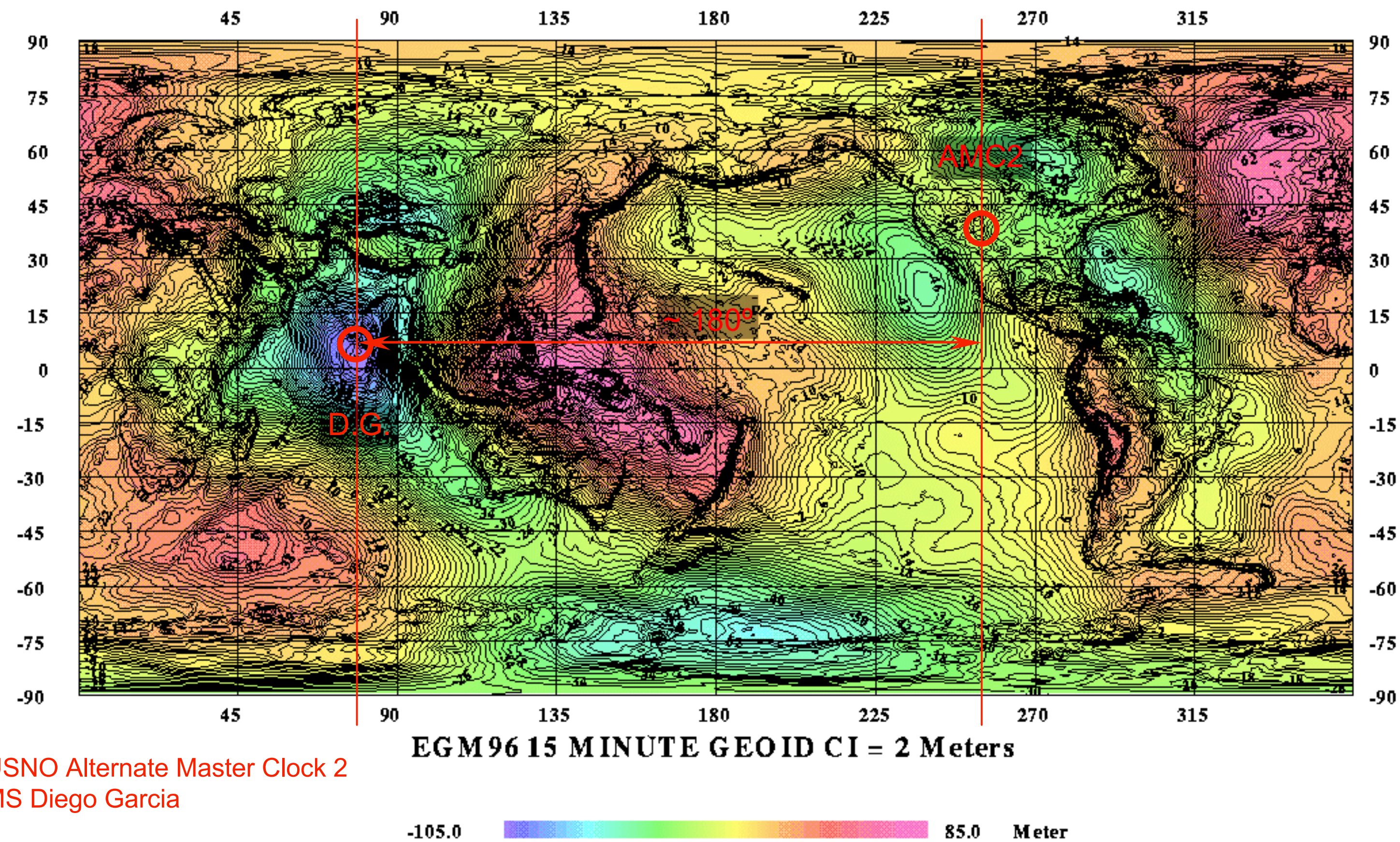
1. Marc Cheves, *American Surveyor*, Web Exclusive (2004).

Continued…

EGM96

The NASA Goddard Space Flight Center (GSFC), the National Imagery and Mapping Agency (NIMA), and the Ohio State University (OSU) have collaborated to develop an improved spherical harmonic model of the Earth's gravitational potential to degree 360. The new model, Earth Gravitational Model 1996 (EGM96) incorporates improved surface gravity data, altimeter-derived anomalies from ERS-1 and from the GEOSAT Geodetic Mission (GM), extensive satellite tracking data – including new data from Satellite laser ranging (SLR), the Global Positioning System (GPS), NASA's Tracking and Data Relay Satellite System (TDRSS), the French DORIS system, and the US Navy TRANET Doppler tracking system – as well as direct altimeter ranges from TOPEX/POSEIDON (T/P), ERS-1, and GEOSAT. The final solution blends a low-degree combination model to degree 70, a block-diagonal solution from degree 71 to 359, and a quadrature solution at degree 360. The model was used to compute geoid undulations accurate to better than one meter (with the exception of areas void of dense and accurate surface gravity data) and realize WGS84 as a true three-dimensional reference system. Additional results from the EGM96 solution include models of the dynamic ocean topography to degree 20 from T/P and ERS-1 together, and GEOSAT separately, and improved orbit determination for Earth-orbiting satellites.

NASA/NIMA, "11. The EGM96 Geoid Undulation With Respect to the WGS84 Ellipsoid", The Development of the Joint NASA GSFC and the National Imagery and Mapping Agency (NIMA) Geopotential Model EGM96, NASA/TP-1998-206861 (1998).



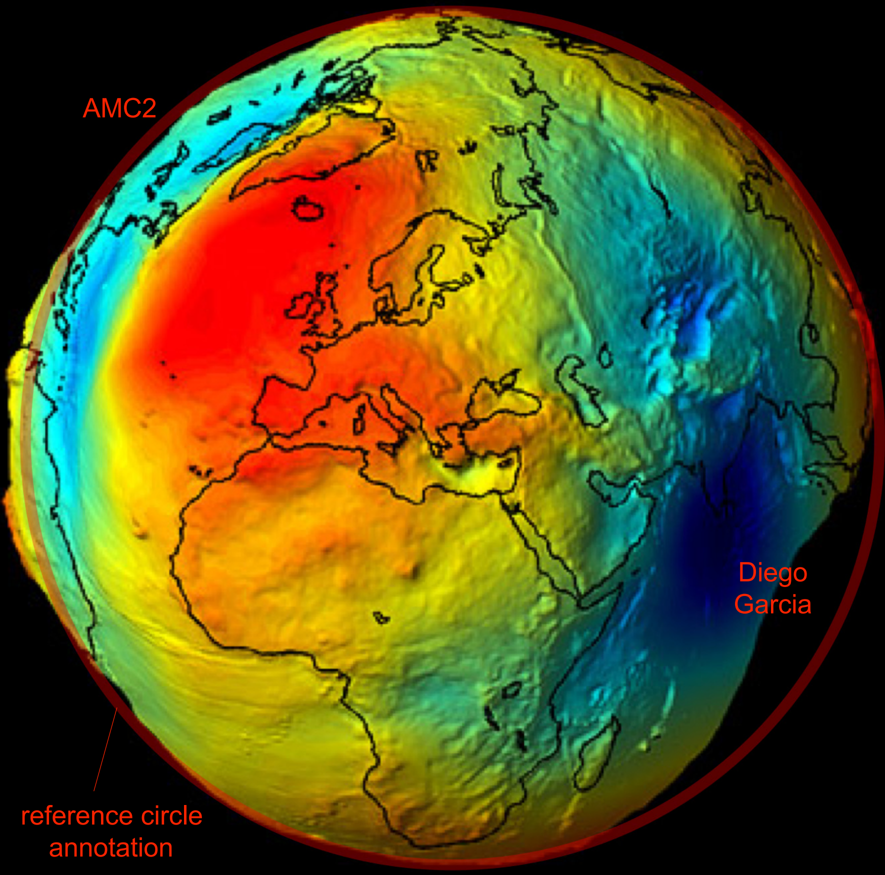
AMC2 : USNO Alternate Master Clock 2
D.G. : MS Diego Garcia

Continued…

GPS geodesy

The accuracy for dynamic geodesy and—to a large extent—all space geodesy, is dependent on accurate positioning of the satellite. In turn, satellite orbit computation accuracy (and satellite ephemeris accuracy) is dependent on the accuracy of the space geodesy. Satellite observations made from the ground can be used accurately only if the ground station locations are known accurately, while the orbit itself can be computed accurately only if all of the forces governing the satellite motion are known. The early dynamic geodesists observed satellite prediction errors and made bootstrap corrections to the gravity models. GPS benefited greatly from the existing WGS gravity model. Techniques that eliminate common-mode errors among ground locations provide improved accuracy over limited distances, but they still depend on satellite position accuracy. GPS geodesy, like GPS navigation, relies on the accuracy, quality, and timeliness of the orbit computation and prediction.

Alan G. Evans *et al*., “The Global Positioning System Geodesy Odyssey”, *Navigation, Journal of the Institute of Navigation*, **49**, (2002), p. 8.



Amplified 3-D view of the current Geoid model, courtesy ESA

Recall that the anomalous results of the Galileo-Ganymede flyby were classified as “gravity anomalies”. This is a term that may be conveniently used to describe observed unmodeled variations in data that would otherwise be unexplained. Here we see Earth’s ‘gravity anomalies’, which do not actually exist, at least at this magnitude. In order for the Earth’s spin to be free of significant non-precessional wobbling, the Geoid must be remarkably smooth. Since the Earth is free of such wobbling, we know that the Geoid is free of the “wild undulations” that are now incorrectly modeled.

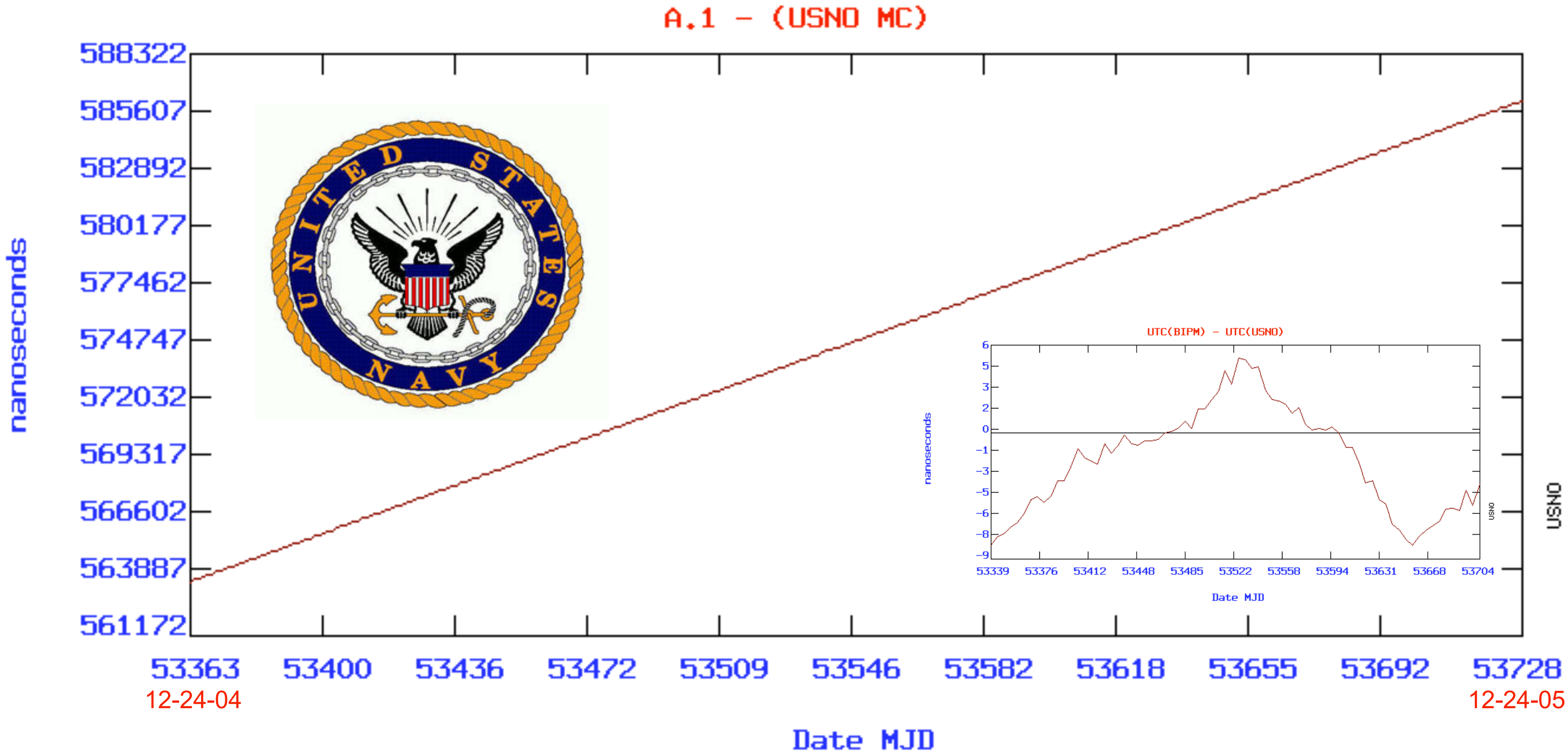
People implicitly trust their $10 calculator to always give the right answer.—The GPS system is a $15 billion ‘calculator’, but because it incorporates an incorrect space-time metric it is essentially slightly ‘broken’ and so effectively implies that Malé Airport is 90 meters under water. Because this is obviously not true, we have a “gravitational anomaly” and a Geoid that looks like a worn dog toy. There is no possibility that the Earth’s Geoid is anything like this model. Rather, the Earth’s observed dynamical behavior implies that the Geoid is remarkably smooth.

Application of the new metric to satellite geodesy measurements and analysis will result in an appropriately smooth Geoid reflecting empirical reality.

It is not a coincidence that the giant ‘bite’ out of the Geoid is associated with MS Diego Garcia, at the approximate antipode to the master GPS atomic clock (AMC2) in Colorado, USA.

Intrinsic instability of UTC

The *GTR* effect implies that a geographically distributed clock set is fundamentally unstable and that it is physically impossible to synchronize two geographically separated clocks at nanosecond resolution. Therefore, after correcting for known effects, a clock ensemble at the BIPM (Bureau International des Poids et Measures) in Paris is found to record time somewhat slower in direct comparison to a clock ensemble at the USNO (US Naval Observatory) in Washington, D.C. However, the opposite is also true; the USNO clock ensemble is found to record time somewhat slower in direct comparison to a clock ensemble in Paris. This seemingly paradoxical empirical fact is a reflection of the geometric properties of time. It follows that the *politically* motivated idea that the global time reference should be established by employing a statistically averaged *globally distributed* clock ensemble with 'contributions' from various nation states is not consistent with the requirements of nature. A single *geographically localized* clock ensemble is the only possible means of achieving an accurate terrestrial time reference with known rate offsets being applied as a function of the distance to the global reference clock. The following graph shows that the USNO unsteered internal time reference A.1 is consistently faster than the USNO master Clock steered to UTC(BIPM). The inset shows the instability between the two steered time references UTC(BIPM) and UTC(USNO). These observations may be correlated with the observations by Bahder of periodic inconsistencies between GPS and USNO Master Clock time scales.



Electrodynamics

- Classical electrodynamics implies that an accelerating charged particle radiates.
- EEP: So, how come a charge *at rest* in a gravitational field does not radiate? After all, it *is* being accelerated by gravity.
- It appears that acceleration, *per se*, does not cause the charge to radiate, so what does cause the charge to radiate?

Dynamical gravitational systems

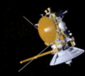
- The fundamental cause of the *GTR* effect is relativistic time dilation, i.e., the *geometry of time* changes over the path.
- The energy dissipation must also apply to mass-energy as well as photons.
- This phenomenon implies spindown and secular orbit decay.
- Energy conservation implies radiation.

Spindown

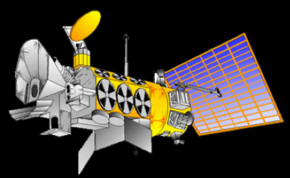
- Rotation of a star, planet, or any mass involves translation of the mass-energy transverse to its own gravitational field.
- The *GTR* effect implies that angular momentum is not conserved.
- Spindown is accompanied by observable ‘gravitational radiation’.
- Observed harmonics of local Solar System origin in the CMBR imply that this radiation occurs in the microwave band.

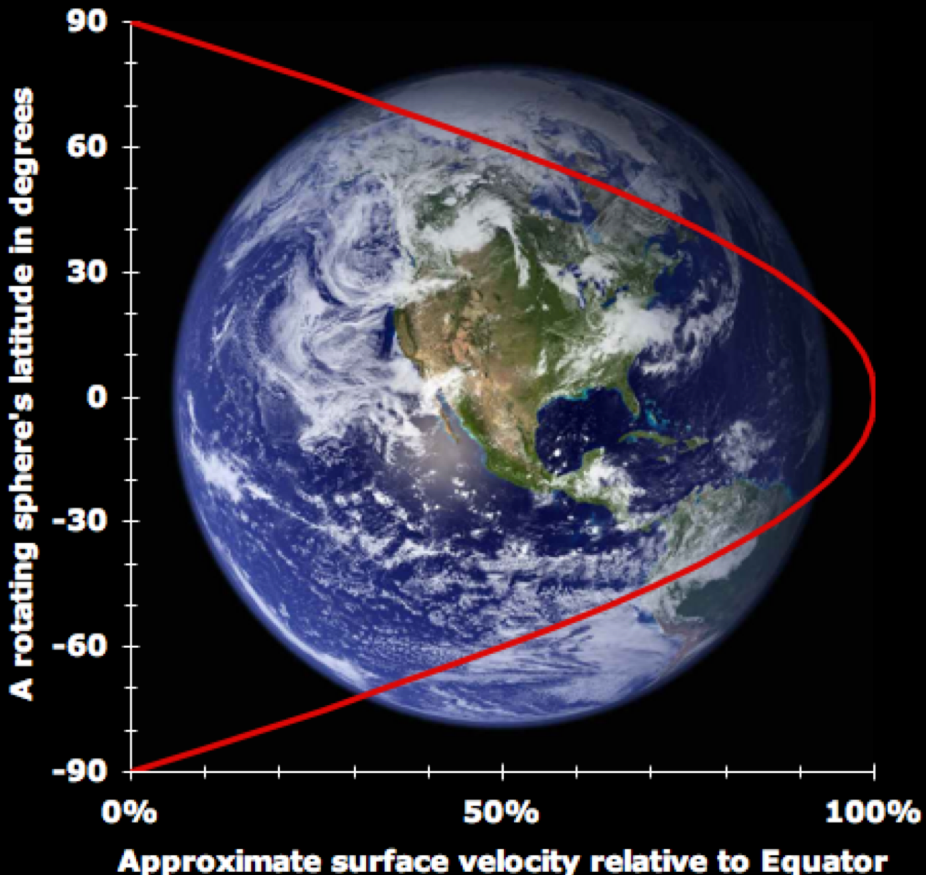
Earth's spindown

- The Earth's observed secular loss of angular momentum increases the length of day by 2.3 milliseconds per century.
- This corresponds to a secular power dissipation in the current epoch of 3.6×10^{12} Watts, which is an order of magnitude greater than the power associated with the secular acceleration of the Moon (2.4×10^{11} Watts).
- It is well-known that pulsars and other stars similarly lose angular momentum at a rate that defies conclusive explanation.
- No *energy dissipation phenomenon* has been identified that balances the Earth's spindown energy budget.



μ-wave spin signature





Upon examination, data from a passive microwave radiometer, ideally in a polar orbit around a planet, will reveal a microwave radiation brightness signature that is proportional to the surface velocity profile. The total energy dissipated will correlate to the observed secular spindown.

The DoD's Defense Meteorological Satellite Program (DMSP) Special Sensor Microwave/Imager (SSM/I) operates at 4 frequencies between 19.35 & 85.5 GHz and may prove an ideal instrument to observe the predicted effect for the Earth.

The RADAR instrument on the Cassini spacecraft now orbiting Saturn, which operates at 13.78 GHz might also be used to independently observe the predicted effect.

Terrestrial radio telescopes may observe a far more subtle signature for the Moon.

Secular orbit decay

- Orbital motion involves translation of mass-energy transverse to the gradient of the host gravitational field.
- Orbits decay due to the *GTR* effect.
- Orbit decay is accompanied by observable ‘gravitational radiation’.
- This radiation is undoubtedly electromagnetic and occurs in the microwave band.

Energy conservation due to orbit decay

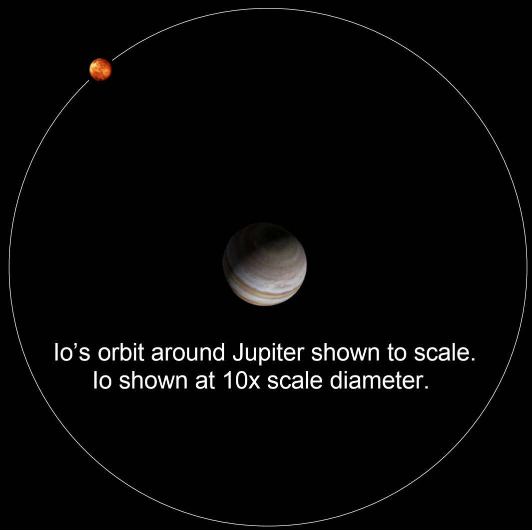
- For orbiting bodies, the same gravitational energy phenomenon causing spindown causes secular orbital decay with the energy being dissipated in the form of radiated electromagnetic energy.
- Orbit eccentricity, such as that of our Moon $(e = 0.055)$ will cause a distinct dynamic flux pattern whereby the EM brightness of the orbiting body is noticeably greater at perigee than at apogee.
- Due to its dominant gravitational relationship with the Sun, the Moon is receding from the Earth rather than suffering *terrestrial* orbit decay, however this does not change the observable.
- Accordingly, the EM brightness of the Moon in the microwave region of the spectrum is predicted to exhibit a periodicity of 27.3 days with peak brightness occurring at perigee.

Migration of Io

Consider a body in a circular orbit, which then always travels transverse to the gravitational gradient. The amended space-time metric implies that due to relativistic effects, such a body must in fact constantly lose energy, thus the circle is actually a subtle spiral. The metric, itself, immediately implies a decay of the semimajor axis of all orbits and a radiative phenomenon to balance the energy budget, i.e., 'gravitational radiation'. Moreover, the nature of that radiation is clear; rather than esoteric, it must be electromagnetic and therefore readily detectable, for the rate of energy dissipation is far higher than previously anticipated.

The mass of Jupiter is over 300 times that of Earth and its radius over 11 times. Its period of rotation is just 9.9 hours. The innermost large moon, Io, has a mass about 20% larger than our Moon. Io orbits just 5 Jovian radii away from the surface in a nearly perfectly circular orbit ($e = 0.004$) that is aligned with the Jovian equator (inclination 0.04º). The Newtonian force of Jupiter's gravitation on Io is well over three thousand times that of the Sun. In contrast, our Moon, with a semimajor axis of about sixty Earth radii and much closer to the Sun than Io, is gravitationally bound to the Sun more than twice as strongly as it is to the Earth.

If there is a perfect candidate in the Solar System to demonstrate tidal dissipation, it is Io. As Jupiter spins faster than the orbital motion of Io, this moon must raise a tide on Jupiter. The resulting tidal bulge will lead Io, transferring angular momentum to the moon while spinning down Jupiter. Thus, Io should not only be seen to recede from Jupiter, but at an unambiguous rapid rate. However, modern observations confirm the baffling 1928 discovery by Willem de Sitter of a substantial secular *decrease* in Io's orbital period as indicated by an anomalous advance in longitude. The observed recalcitrant behavior of Io is indicative of a very significant *counteracting* phenomenon that overcomes the effect of tidal dissipation for Io. This phenomenon is the gravitational transverse redshift effect, caused by the complimentary relativistic phenomena of circuitous space and time dilation.



Io's orbit around Jupiter shown to scale.
Io shown at 10x scale diameter.

From reanalysis of 17th century and 20th century eclipse observations, with three different models for the Earth's rotation, and from the use of both longitude comparison and mean motion comparison, we find that Io has a fractional acceleration of $(4.54\pm0.95)\times10^{-10}$ yr^{-1}. If Io can be considered a Keplerian oscillator, its orbital semi-major axis decreases by 13 *cm*/*yr*.

Samuel J. Goldstein & K.C. Jacobs, "A Recalculation of the Secular Acceleration of Io", *Astronomical Journal* **110**, 3054-3057 (1995).

Our determination of [the mean motion rate of change] is in reasonable agreement with the values 3.3±0.5 (from de Sitter, published in 1928) and 4.54±0.95 (from Goldstein & Jacobs, published in 1995), both of which were derived from analyses of eclipses of the satellites by Jupiter and some photographic observations. However, it conflicts with the value -0.074±0.087 found by Lieske (published in 1987) from Jovian eclipse timings. Our results imply that Io is now spiraling slowly inward, losing more orbital energy from internal dissipation than it gains from Jupiter's tidal torque.

Kaare Aksnes & Fred A. Franklin, "Secular Acceleration of Io Derived From Mutual Satellite Events", *Astronomical Journal* **122**, 2734-2739 (2001).

Phobos close-up
~ 11.2 *km* diameter

Migration of Phobos & Deimos

The dot in the center of the yellow circle shows the scale size of Phobos relative to Mars (background). The orbits of the two moons are shown to scale in the diagram on the right.

The nearest natural planetary satellites to Earth other than the Moon are Phobos and Deimos of Mars. Judging by their size, shape and composition, these satellites are perhaps best categorized as captured carbonaceous asteroids rather than moons as one may interpret that word by terrestrial standards. Phobos has an average diameter of 11.2 *km* while that of Deimos is just 6.1 *km*. Due to their tiny size, it is obvious that tidal dissipation plays no role in the ephemerides of these moons. Also, both satellites orbit well above any vestiges of Mars' thin atmosphere. The fact that Phobos is observed to be spiraling down to Mars with its orbital radius *decreasing* by about 4 centimeters per year is a clear indication of the identical effect acting on Jupiter's Io. At 23,459 *km*, the semimajor axis of Deimos is 2.5 times that of Phobos. Contrary to Phobos, it exhibits an apparent very small annual decrease in its orbital angular velocity corresponding to a non-Keplerian retardation in longitude of $\sim 7 mas^{*}\ yr^{-2}$. This is an indication of a migration behavior dominated by the Sun rather than the host planet, as we shall see is also true for Earth's Moon.

G. A. Neuman *et al.*, "Refinement of Phobos Ephemeris Using Mars Orbiter Laser Altimeter Radiometry", *Lunar and Planetary Science* **35**, 1820 (2004)

R. A. Jacobson, S. P. Synott & J. K. Cambell, "The orbits of the satellites of mars from spacecraft and Earth-based observations", *Astronomy & Astrophysics* **225**, 548-554 (1989).

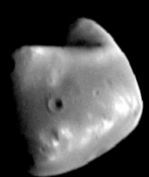
D. H. P. Jones, A. T. Sinclair & I. P. Williams, "Secular acceleration of Phobos confirmed from positions obtained on La Palma", *Mon. Not. Royal Astron. Soc.* **237**, 15-19 (1989).

Orbits of the moons relative to the planet

Phobos orbit
9,378 *km*

Deimos orbit
23,459 *km*

* milliarc-second



Deimos close-up
~ 6.1 *km* diameter

Mars as seen by the Hubble Space Telescope

STELLA
24 *cm*

LAGEOS
60 *cm*

Migration of geodetic satellites

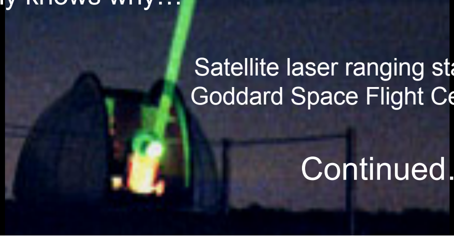
LAGEOS-1 (Laser GEOdynamics Satellite) is a 407 *kg*, 60 *cm* diameter passive spherical Earth satellite that was launched on 4 May 1976 into a nearly circular ($e = 0.0045$) high inclination orbit ($i = 109.8^o$) with perigee altitude of 5860 *km*. It is covered with over four-hundred 3.8 *cm* diameter cube-corner laser retroreflectors. The cylindrical beryllium copper core and aluminum spherical shell were chosen specifically to reduce the effects of the Earth's magnetic field on the satellite's orbit. No instrumentation or stabilization mechanism is on board; The LAGEOS is very much like a tiny spinning 'silver moon'. The satellite is designed to reflect precisely timed laser pulses from ground stations for the purpose of determining the relative location of the satellite and the ground station. With an accurately modeled and measured trajectory, arguably affected almost exclusively by gravity, the satellite is intended to provide a stable reference frame uniquely suited to geodesy and the study of crustal dynamics. Its altitude of almost 6000 kilometers was chosen with the idea that no atmospheric drag whatsoever would act on the satellite…

> LAGEOS' orbit is the most accurately modeled of any satellite [Cohen and Smith, 1985]. However, after subtracting out most of the known forces acting on the satellite, such as the gravitational attraction of the sun and the moon, direct solar radiation pressure, etc. there is still a residual along-track acceleration which remains to be explained…
>
> [The unexplained along-track acceleration] clearly acts like a drag and has a mean value of $-3.33\times10^{-12}\ m\ s^{-2}$. It brings LAGEOS closer to the earth by 1.2 $mm\ d^{-1}$. Moreover, there are fluctuations in the acceleration which can be as large as the mean value. At times, *S* drops almost to zero, as in March 1983. Most of the fluctuations are obviously correlated with the sun-orbit geometry: the largest ones occur when LAGEOS spends time in the earth's shadow. [1]

> The semimajor axis of Lageos's orbit exhibits a secular decrease upon which periodic variations are superimposed. This secular decrease cannot be explained by gravitational effects, radiation pressure, the Poynting-Robertson effect, and various electromagnetic effects. On the other hand, charge drag appears to be a possible cause. However, the problem is not definitely settled. [2]

In part to try to understand the peculiar unmodeled behavior of LAGEOS-1, the Italian Space Agency (ISA) built a second satellite, LAGEOS-2, which is almost an identical twin to the original. It was launched on 22 October 1992 by shuttle mission STS 52 and put into a substantially less inclined and slightly more eccentric and lower-altitude orbit ($i = 52.6^o$, $e = 0.0135$) with perigee altitude 5620 *km*. As the second satellite exhibits a marked difference in time evolution of the unmodeled acceleration from the first, this indicates that the orbit inclination is a significant factor in the manifestation of the effect. In 1989, the former Soviet Union launched Etalon 1 and 2, two larger (1.3 *m* dia., 1415 *kg*) spherical geodetic satellites at identical inclination ($i \approx 65^o$, $e \approx 0.0006$) with perigee altitude 19,129 *km* and ~121º out of phase. France's Centre National d'Etudes Spatiales (CNES) launched the first geodetic satellite, Starlette, in February 1975 followed by Stella in September 1993. These smaller satellites are 24 *cm* in diameter, having 60 cube-corner reflectors and weighing under 50 *kg*. They are in circular orbits at about 800 *km* altitude with the former at an inclination of 49.83º and the latter at 98.6º. The Japanese Ajisai satellite, weighing 685 *kg*, was launched into a 1500 *km* orbit at 50º inclination in August 1986. All of the geodetic satellites are 'falling out of the sky' and nobody really knows why…

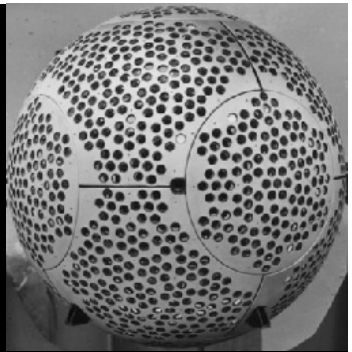
1. David Perry Rubincam, "LAGEOS Orbit Decay Due to Infrared Radiation From Earth", *Journal of Geophysical Research* **92**, 1287-1294 (1987).
2. G. Alfonso *et al.*, "Reassessment of the charge and neutral drag of Lageos and its geophysical implications", *Journal of Geophysical Research* **90**, 9381-9398 (1985).



Satellite laser ranging station
Goddard Space Flight Center

Continued…

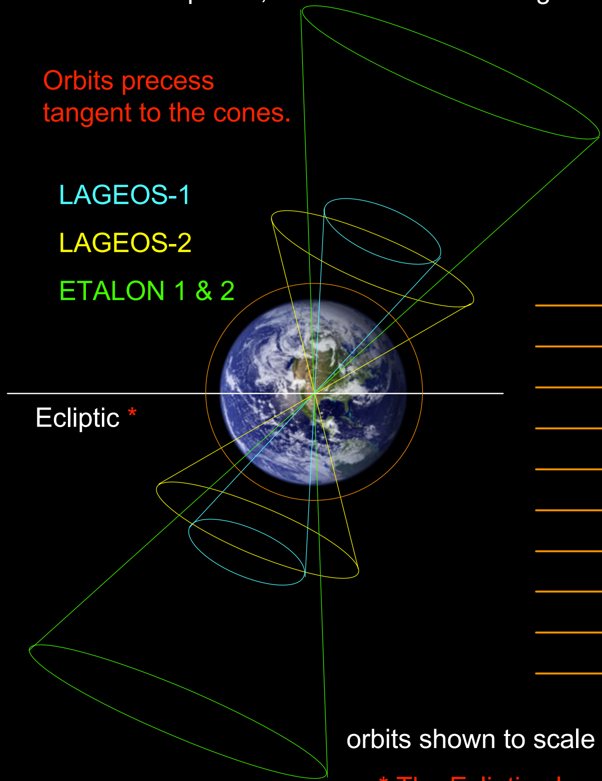
ETALON
1.3 m



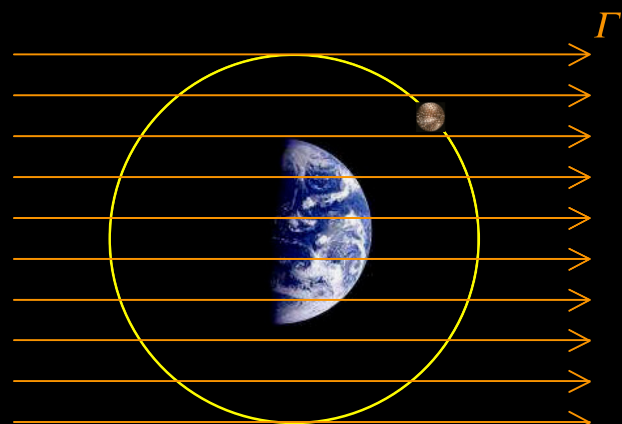
Mysterious dynamics explained

The geodetic satellites do not just fall out of the sky, they 'dance' while they are doing it. Sometimes they go faster and sometimes they go slower in an exasperating cycle that seems to have no identifiable pattern other than some correlation to being more or less in the Sun. This is why it seemed reasonable to assume that sunlight had something to do with the observed behavior. Actually, it does in a roundabout way, but photons have nothing to do with it. The critical factor that dictates the observed *dynamical* behavior of all geodetic satellites is the vector dot product of the satellite velocity vector $\mathbf{v}_s$ and the solar gravitational gradient Γ. This is dependent on the obliquity of the orbit relative to the Ecliptic and the relationship between Γ and the satellite angular momentum vector ω. While the *GTR* effect of the Earth's gravitational field is very nearly constant for a geodetic satellite in a circular orbit, the solar *GTR* effect varies in a complex pattern associated with the motion of the Earth around the Sun combined with the natural precession of the satellite's orbit relative to the celestial sphere . That precession has a typical period of several years that is not an integer multiple of a sidereal year. Therefore, the observed dynamical behavior of the satellite has little correlation with Earth's seasonal calendar. The satellite inclination is an important factor that affects the observed dynamic behavior, but only indirectly. Because the Etalon satellites are ~121° out of phase, it is clear from the diagram that their respective orbits' relationship to the ecliptic is radically different. So, in spite of being at identical inclination, their real-time behavior will be radically different. It is also immediately obvious that the greater inclination of LAGEOS-1 (blue cone) will constrain its dynamic behavior to a greater degree than LAGEOS-2 (yellow cone) whose orbit plane 'swings' over a greater angle relative to the Ecliptic. Both French satellites, which orbit at the altitude indicated by the orange circle (orbit inclination and precession not shown) can be expected to have huge residuals due to their relative proximity to the Earth, implying a stronger gravitational field combined with a higher angular velocity.

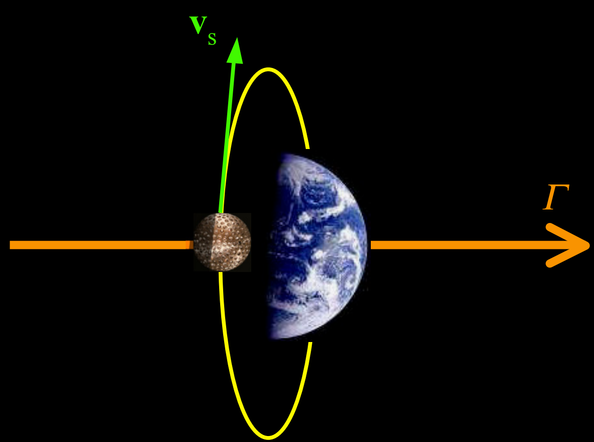
Orbits precess tangent to the cones.



orbits shown to scale

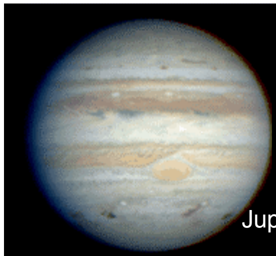


$$0 \le \cos\theta \{\mathbf{v}_s \cdot \Gamma\} \le 1$$

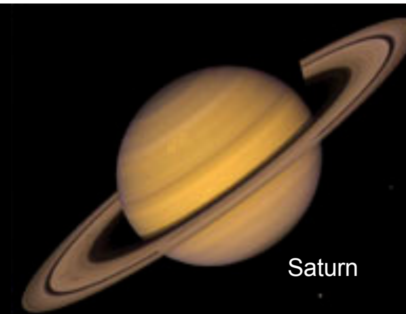


$$\cos\theta \{\mathbf{v}_s \cdot \Gamma\} = 0$$

* The Ecliptic plane is the plane of the Earth's orbit around the Sun.


Jupiter

Migration of planets


Saturn

planets are shown to scale relative to Earth ⟶ 

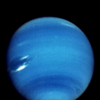
If motion transverse to the gravitational gradient causes a secular energy loss, then orbits cannot be stable. One would then expect planets to gradually migrate towards their host star. The large outer planets of the Solar System (Jupiter, Saturn, Uranus and Neptune) are all too far away from the Sun to experience solar angular momentum transfer, which would tend to counteract the solar *GTR* effect, causing climate-changing *oscillations* in the semimajor axis of a planet's orbit. A planet that is closer to the Sun (Jupiter) than a more outlying planet (Saturn) orbits faster and in a stronger region of the Sun's gravitational field, so it will migrate towards the Sun faster.

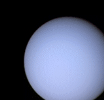
…the authors show that the passage of Jupiter and Saturn through a 1:2 mean-motion resonance (MMR) can account for the orbital spacings, eccentricities and inclinations of all four giant planets. … The authors' find that the passage of Jupiter and Saturn through this resonance can excite their eccentricities and inclinations to current levels. However, Jupiter and Saturn are currently rather far from the 1:2 resonance — the ratio of their current orbital periods is near 1:2.5 — so the implication here is that these planets have since migrated through 2:1 to their present positions. This is a remarkable concept, because we usually think of the planets' orbits as being rather static and changing little over time.

John Hahn, "When giants roamed", *Nature* **435**, 432-433 (2005); also see *Nature* **435**, 459-469 (2005).

We show that the peculiar eccentricity distribution of the Hilda asteroids, objects that librate at the 3:2 mean motion resonance with Jupiter, as well as their distribution about the resonance itself, can be nicely reproduced from captured field asteroids if Jupiter has migrated sunward by about 0.45 AU* over a time greater than 100,000 years. The latter is a lower limit and longer times are more likely, while the former quantity depends to some degree on the initial eccentricity distribution, but a fit to the observations fails unless it lies in the range of 0.4 to about 0.5 AU, where the lower value is particularly well established

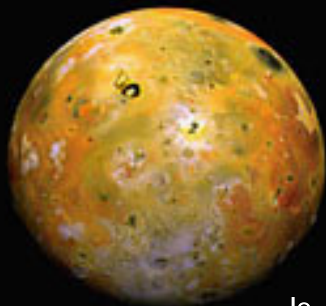
Fred A. Franklin, Nikole K. Lewis, Paul R. Soper & Matthew J. Holman, "Hilda Asteroids as Possible Probes of Jovian Migration", *Astrophysical Journal* **128**, 1391-1406 (2004).


Neptune


Uranus

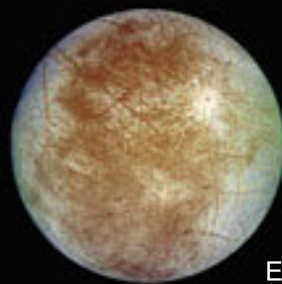
* 1 AU ≡ 1 Astronomical Unit, the mean radius of the Earth's orbit or ~150 million kilometers.

The migration of the Galilean satellites J1 - J3 into a Laplace resonance



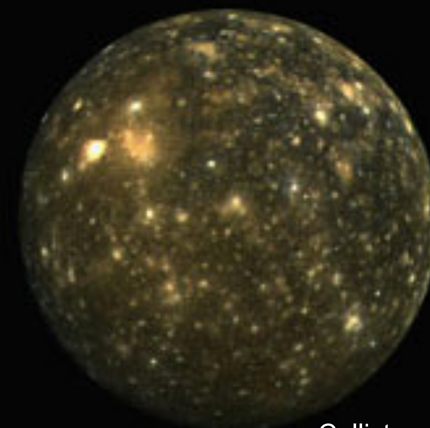
Io - J1

Named for Galileo Galilei, who first observed these four moons with his telescope in 1610. There are many other smaller Jovian moons, but they are rather like captured asteroids.



Europa - J2

Ganymede - J3



Callisto - J4

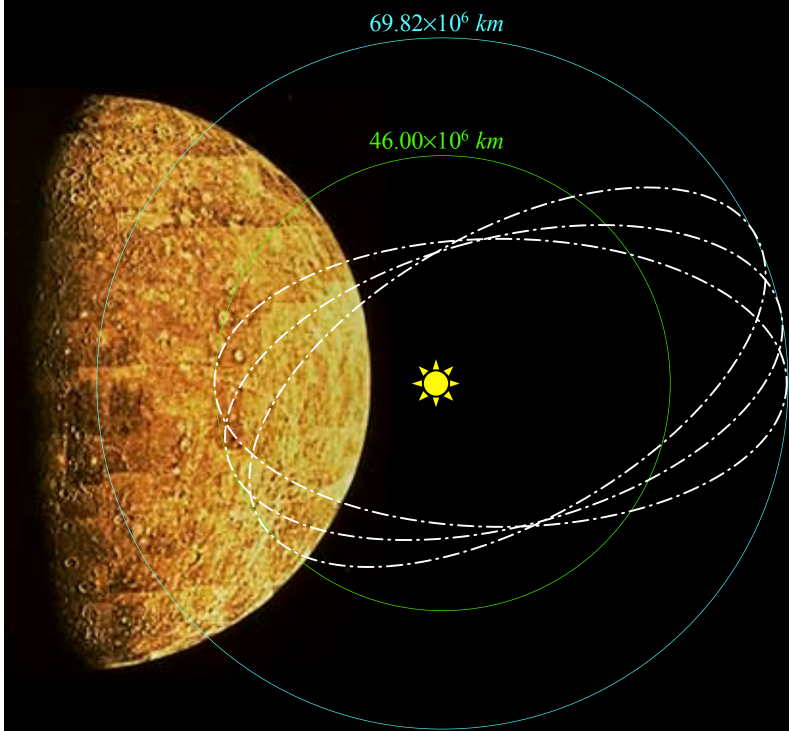
The mean motion n of an astronomical body in an elliptical orbit is equal to the average angular frequency, which is inversely proportional to the orbital period T ($n \equiv 2\pi/T$). When n has a subscript, it denotes the satellite number, starting with the innermost satellite, e.g., 1 for Io of the Galilean moon set. It is well known that Io, Europa and Ganymede exhibit a Laplace resonance whereby $n_1 - 3n_2 + 2n_3 = 0.0000^\circ$ per day. For the observed configuration of a stable point of conjunction to evolve, it is certainly the case that a differential migration of the satellites from their random primordial configuration was required; however, no satisfactory theory exists that describes how this evolution came about while avoiding higher order resonances.

> On the assumption that the resonance was formed by the action of tidal forces, we describe what the evolution of the system must have been like before and after the formation of the resonance. However, no satisfactory explanation of the capture into the resonance is found. It seems possible that the system could have been captured into a large amplitude libration, but it is then difficult to explain the present very small amplitude.[1]

The Galilean satellite Laplace resonance implies that a secular inbound migration was required. It is clearly the case that such a migration allows for an initial capture into resonance of two bodies followed by a second capture of the third body. The *GTR* effect of Jupiter's powerful gravitational field is without doubt the instrument of this migration as there are conclusive observations that Io is currently inbound in spite of what must be powerful counteracting gravitational tidal forces.

1. Andrew Sinclair, "The orbital resonance amongst the Galilean satellites of Jupiter", *Celestial Mechanics* **12**, 89-96 (1975).

Perihelion progression of Mercury



The elliptical orbit is drawn inaccurately for illustrative purposes. Perihelion and aphelion distances are drawn to scale.

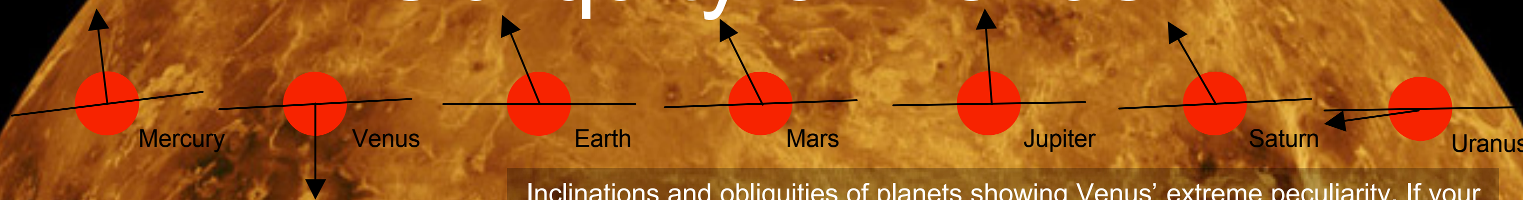
One of the major predictive successes of Einstein's theory was the calculation of the a priori observed but unexplained non-Newtonian perihelion progression of the planet Mercury. There is a bit of mathematical 'wizardry' involved and the fundamental *dynamical* reason for this behavior is not clear. Also, it has been claimed that the Sun has a quadrupole moment that makes a non-relativistic contribution to the motion, which implies that the conventional GR calculation is slightly incorrect. [1]

In no uncertain terms, the amended theory states the following: In the region of the green circle (perihelion), where the gravitational field of the Sun is stronger, Mercury loses slightly more energy relative to the Sun than for the blue circle (aphelion). From a simple Newtonian perspective, the effect is the same as if there were a slight 'braking' action that is greatest at the green circle and least at the blue circle. For each orbit, that 'braking' action brings Mercury ever so slightly closer to the Sun at perihelion, which causes the velocity of the planet to *increase* slightly, advancing the perihelion point of the orbit. It follows that in addition to the perihelion advance of the orbit, the amended gravitational model predicts a secular decrease in the semimajor axis of Mercury's orbit. In other words, all planets tend to very slowly *migrate* in towards their host star, a process that in some fortunate cases (Earth) may be counteracted by solar angular momentum transfer.

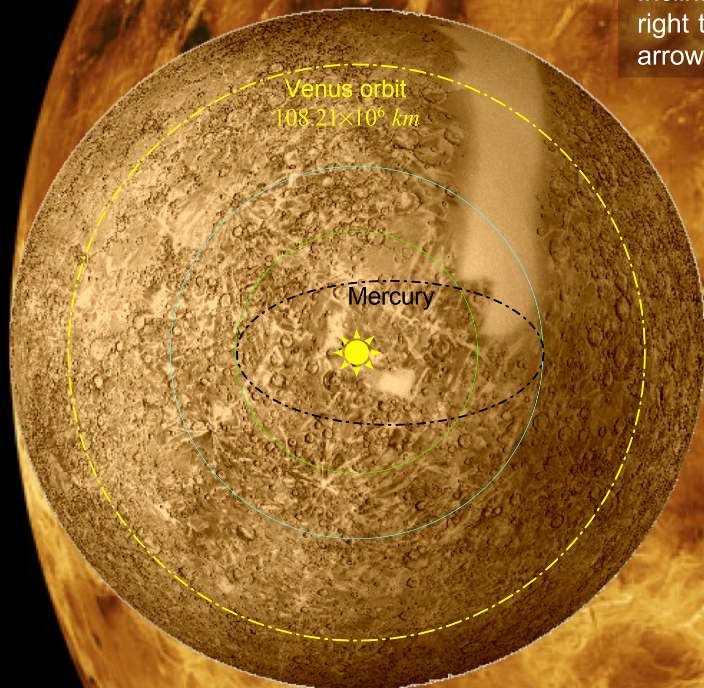
In addition to the observation of Io's anomalous orbital decay, a number of other correlated observed phenomena imply that this idea is indeed an accurate reflection of empirical reality…

[1] Robert H. Dicke, "The Solar Oblateness and the Gravitational Quadrupole Moment", *Astrophysical Journal* **159**, 1 (1970).

Obliquity of Venus



Inclinations and obliquities of planets showing Venus' extreme peculiarity. If your right thumb points with the arrow, then the planet rotates around the axis of the arrow in the direction of that your fingers curl. This is called "the right-hand rule".



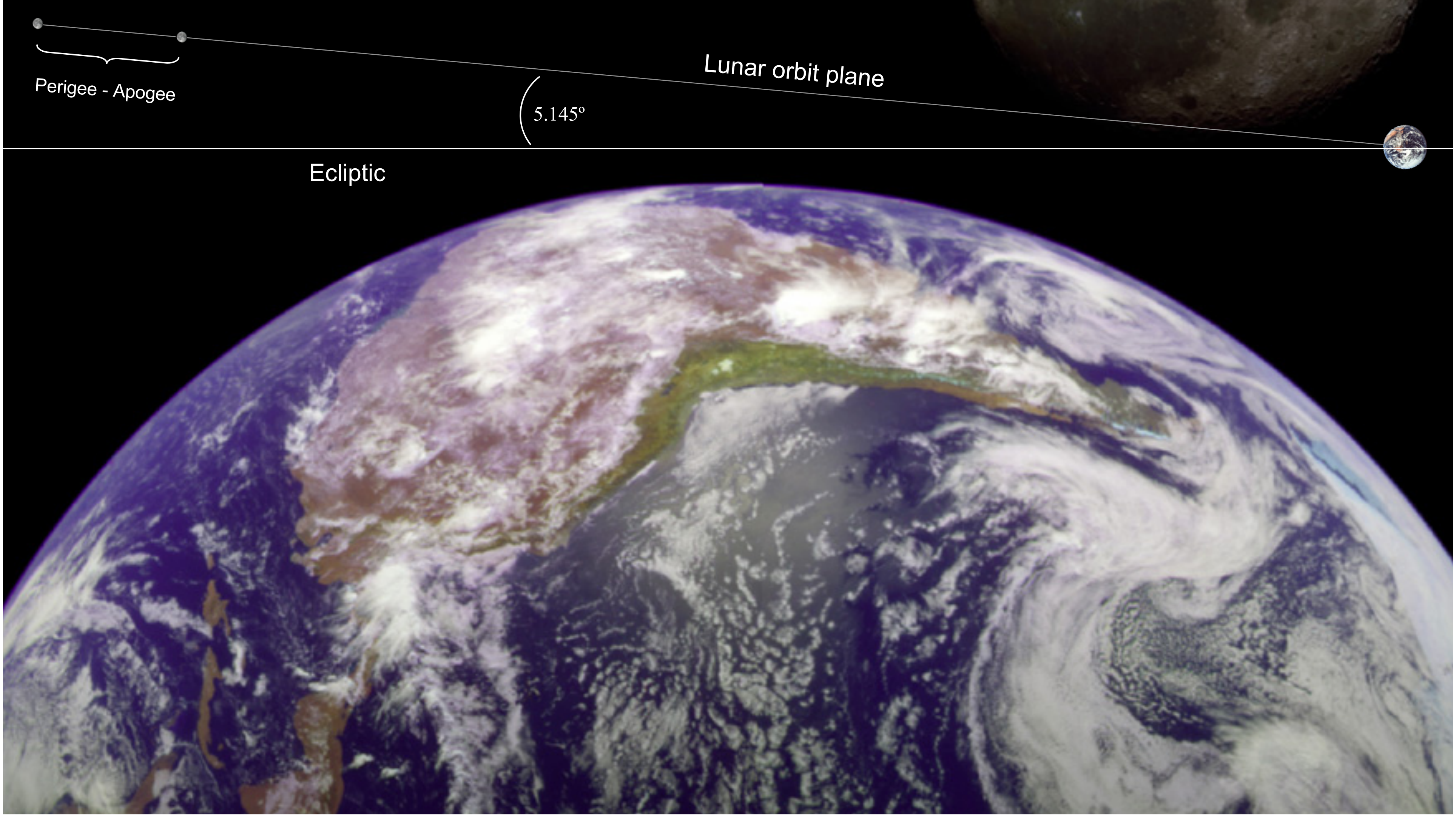
In 1976, Thomas Van Flandern and Robert Harrington of the US Naval Observatory (USNO) published a paper in the journal *Icarus* in which they posited that Mercury is an escaped satellite of Venus. They pointed out that not only is Mercury very moon-like, but Venus exhibits many features consistent with a planet that once experienced strong gravitational interaction and commensurate tidal friction with a moon. These features include a dense, hot atmosphere, mountains and little residual rotation. Moreover, Venus exhibits the grossly peculiar feature of a 177.4° obliquity (axial tilt) and retrograde rotation. It is almost certain that Venus' primordial obliquity was similar to the other planets from considerations of angular momentum in the process of Solar System formation. Therefore, it will have been necessary for its former moon (Mercury) to have been torn away by Solar *GTR*, in order for Venus to have experienced the enormous gravitational forces necessary to tilt its spin axis from the primordial configuration to the currently observed anomalous configuration. It is not difficult to imagine how *GTR* will have caused the Sun to eventually capture Mercury as it accelerated in its recession from Venus with increasing orbital radius from its host planet. It will be shown that modern observation of the secular acceleration of Earth's Moon supports the hypothesis.

Unlike Mercury, which appears to scale relative to the Venus background, Venus' orbit is nearly perfectly circular. The orbit radii for both planets are drawn to scale. The bald patch is an area unmapped by the Mariner 10 spacecraft, which visited the planet in 1974-1975.

Thomas Van Flandern & Robert S. Harrington, "A Dynamical Investigation of the Conjecture that Mercury is an Escaped Satellite of Venus", *Icarus* **28**, 435-440 (1976).

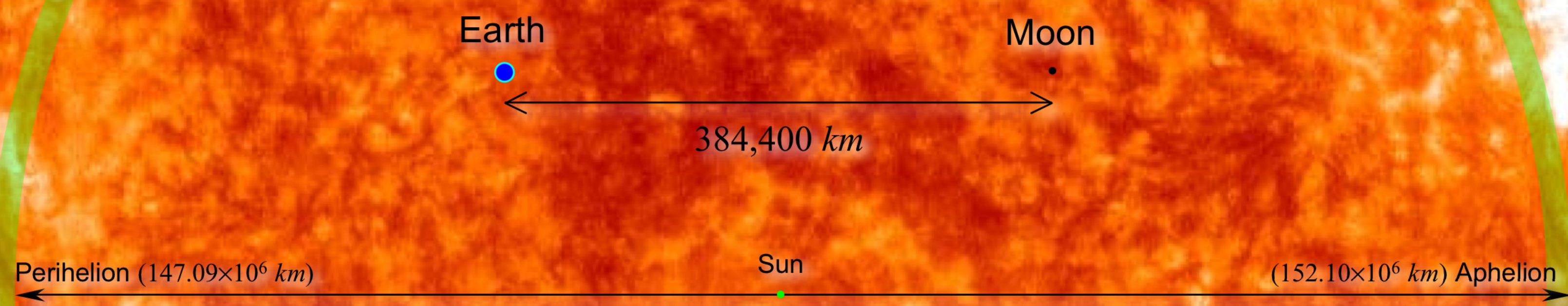
Earth-Moon System

For comparative reference, the background image shows the scale size of the Moon relative to the size of the Earth and below is a scale diagram of the lunar orbit.



Earth and Sun

The Earth, the Moon and the semimajor axis* of the lunar orbit are drawn to scale, relative to the size of the Sun (background).



The Earth's semimajor axis is ~389 times the Moon's distance.

If the green circle represents the Earth's orbit around the Sun, then its width (drawn to scale) represents the radial distinction between perihelion (inner edge) and aphelion (outer edge), which is a distance of just over 5 million *km* or about 3.6 times the diameter of the Sun.

Note that without the *GTR* effect, it is arguably the case that stars could not form, because conservation of angular momentum would prevent the expeditious central accumulation of gas from a rotating self-gravitating cloud of hydrogen gas, igniting thermonuclear fusion.

* **semimajor axis**:
the average distance between orbiting bodies, or
half the sum of the perigee and apogee distances.

The secular acceleration of the Moon

Since Apollo 11 (1969) Lunar Laser Ranging (LLR) has established that the Moon is *receding* from the Earth at a rate of 3.8 *cm*/*yr* in the current epoch. It has been historically assumed that tidal dissipation (angular momentum transfer from the Earth) is responsible for the secular acceleration of the Moon, however there are a number of reasons why this cannot be the case.

- Tidal dissipation implies that the Moon's rate of recession was far greater in the past when the Earth was spinning faster and the Moon was closer to the Earth, putting the Moon catastrophically close to the Earth in the past.
- Tidal dissipation implies that the energy gained by the Moon per unit time is the same as the energy lost by the Earth due to its spindown, but the calculations differ by more than an order of magnitude.
- Tidal dissipation implies a larger perturbing effect when the Moon is at perigee and a smaller effect when it is at apogee, tending to reduce the eccentricity of the Lunar orbit over time, but the orbit has a marked eccentricity ($e = 0.0549$).
- Tidal dissipation implies that the plane of the Moon's orbit would tend to become aligned with the Equatorial plane of the Earth, when instead the Moon's orbit is closely aligned with the Ecliptic plane.

Continued…

Image: NASA

Lunar recession

The first lunar laser reflector (A11) placed near the Apollo 11 Eagle LM at Tranquility Base, July 1969. There are 2 more Apollo reflectors and 2 Russian/French reflectors from the unmanned Luna Program.

The gravitational attraction between the Moon and the Sun is over twice that between the Moon and the Earth. Therefore, the Earth and Moon are rather more like a double-planet system co-orbiting the Sun than a planet and its satellite, e.g., Jupiter and Io. The proposed amendment to Einstein's theory of gravity implies that the Earth-Moon system is constantly losing energy relative to the Sun, though the semimajor axis of their ~150 million *km* solar orbit oscillates over geologic timeframes due to angular momentum transfer from the Sun to the system due to solar tidal dissipation. Because the Moon orbits near to the ecliptic plane, one of the two bodies is generally closer to the Sun than the other. This means that space in the direction transverse to the solar gravitational gradient is slightly more 'stretched' by the Sun for the closer of the two bodies at a given time than the other, so the body closest to the Sun loses a little more energy than the other. While terrestrial tidal dissipation may play some role in the secular acceleration of the Moon, the solar *GTR* effect will have become increasingly dominant, accelerating the recession as the lunar semimajor axis increased over time. The effect will have also driven the lunar orbit closer towards the Ecliptic and increasing eccentricity. So, it is a kind of illusion that the Moon's orbit is somehow being boosted by the Earth. It is really a side-effect of the Earth and Moon experiencing a differential loss of energy relative to the Sun amounting to a difference of 2.4×10^{11} Watts in dissipated power.

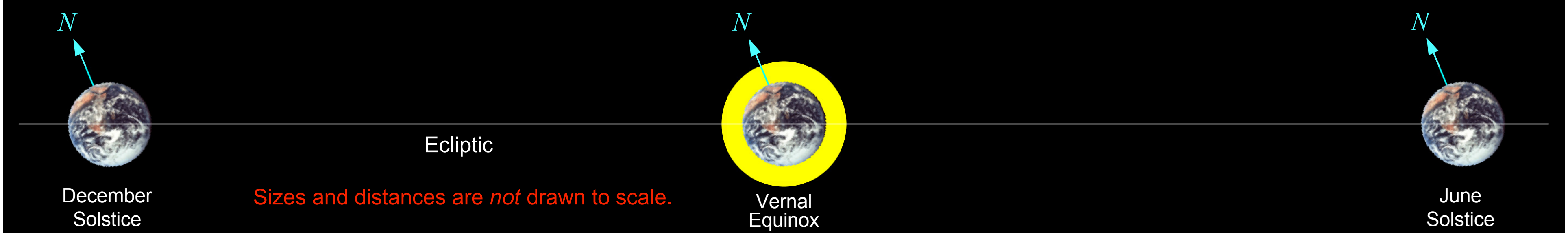
The fact that the secular acceleration of the Moon is driven by solar *GTR*, a relativistic effect of the Sun's gravitational field, and not tidal dissipation, should be empirically verifiable by LLR. If tidal dissipation were responsible for the phenomenon, then the recession rate of the Moon would be greatest at perigee and least at apogee. For the *GTR* effect, just the opposite is true and LLR measurements may confirm that this is the case.

Image: NASA, Mayer

‘Fictitious’ motion of the Equinox

As of 1 January 1998, the International Celestial Reference System (ICRS) replaced the Fifth Fundamental [Star] Catalogue (FK5) which had briefly superceded FK4. The ICRS is unique from previous celestial reference frames as it is based on the observed locations of distant quasars, which exhibit no proper motion. Modern techniques in space astronometry (astronomical position measurement) have essentially eliminated errors and uncertainties in measurement that may have existed for historic measurements. The relativistic gravitational transverse redshift (*GTR*) effect causes previously unmodeled motions of the Earth and planets that can now be definitively identified over relatively short periods of time due to the extreme precision of astronometric measurements and the certainty of their accuracy.

The observation of a non-precessional motion of the Equinox, or what has been called, somewhat ironically, the “fictitious motion of the Equinox” is consistent with unmodeled secular variation in Earth’s mean orbital radius with a corresponding change in its mean orbital angular velocity.



V. V. Vityazev & E. I. Yagudina, “The non-precessional motion of the equinox: a phantom or a phenomenon?”, Journées 2000 - systèmes de référence spatio-temporels. J2000, a fundamental epoch for origins of reference systems and astronomical models, Paris, 18-20 septembre 2000, ed. N. Capitaine, (Paris: Observatoire de Paris, 2001), pp. 42-47.

Yuri B. Kolesnik & C. Johan Masreliez, “Secular Trends in the Mean Longitudes of Planets Derived From Optical Observations”, *Astronomical Journal* **128**, 878-888 (2004).

Orbital period modulations

With surprising and mysterious regularity, life on Earth has flourished and vanished in cycles of mass extinction every 62 million years, say two UC Berkeley scientists who discovered the pattern after a painstaking computer study of fossil records going back for more than 500 million years…

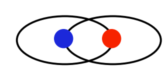
"We've tried everything we can think of to find an explanation for these weird cycles of biodiversity and extinction," Muller said, "and so far, we've failed." …

But the cycles are so clear that the evidence "simply jumps out of the data," said James Kirchner, a professor of earth and planetary sciences on the Berkeley campus who was not involved in the research but who has written a commentary on the report that is also appearing in *Nature* today. …

Said Muller: "We're getting frustrated and we need help. All I can say is that we're confident the cycles exist, and I cannot come up with any possible explanation that won't turn out to be fascinating. There's something going on in the fossil record, and we just don't know what it is

David Perlman, "Mass extinction comes every 62 million years, UC physicists discover", *The San Francisco Chronicle*, 10 March 2005.

The careful timing of [binary star] eclipses can reveal orbital period changes of order a part in 10^5–10^6 because deviations from an assumed ephemeris can build up over many orbits, and many systems have observational records spanning decades or more. These observational records reveal a surprising result: systems that show period changes of alternating sign (orbital period modulations) are common.



James A. Applegate, "A Mechanism For Orbital Period Modulation in Close Binaries", *Astrophysical Journal* **385**, 621-629 (1992).

Terrestrial Orbit Oscillation

The semimajor axis of an orbit is fundamentally unstable according to the amended relativistic gravitational model. Evidence of this is found in close binary star systems, which naturally exhibit more rapid time evolution of orbital period modulations than those suggested for the Earth. Period increase is caused by angular momentum transfer, which boosts the semimajor axis of the orbit while spinning down the respective stars through either gravity induced tidal dissipation or perhaps magnetic field interaction. Period decrease is undoubtedly caused by the *GTR* effect, which also causes general inbound planetary migration.

Perihelion ($147.09 \times 10^6\ km$) Sun ($152.10 \times 10^6\ km$) Aphelion

If the Earth was orbiting within the blue circle, it would be a lot colder, and if it were orbiting within the yellow circle, it would be a lot warmer. The magnitude of periodic terrestrial semimajor axis variations shown here is not suggested to be accurate. However, from geologic evidence, the period of the oscillation is estimated to be on the order of 100 million years. When Earth orbits in the blue circle, there are miles of ice at the Equator. When it orbits in the yellow circle, Antarctica is entirely free of ice and large inland seas are pervasive. Secular loss of solar angular momentum, which counteracts solar *GTR*, implies faster inbound migration and deeper penetration for each subsequent oscillation of Earth's semimajor axis. There is no imminent danger to the human race, at least for perhaps millennia, so don't be a 'Chicken Little'. However, it is clear that species survival requires a space-faring civilization.

Orbit of Venus
Temp. ~ 480˚C

Snowball Earth

Ocean Drilling Program Leg 171B was designed to recover a series of ‘critical boundaries’ in Earth history in which abrupt changes in climate and oceanography coincide with often drastic changes in the Earth’s biota. Some of these events such as the Cretaceous-Paleogene (K-T) extinction and the late Eocene tektite layers are associated with the impacts of extraterrestrial objects, like asteroids or comets, whereas other events, including the benthic foraminifer extinction in the late Paleocene and the mid Maastrichtian extinction events, are probably related to intrinsic features of the Earth’s climate system. Two of the critical boundaries, the early Eocene and the late Albian, are intervals of unusually warm climatic conditions when the Earth is thought to have experienced such extreme warmth that the episodes are sometimes described as ‘super-greenhouse’ periods.

ODP Leg 171B Shipboard Scientific Party, “Critical Boundaries in Earth's History - and the K-T Boundary”, *JOIDES* * *Journal* **23**, 1-10 (1997); http://www.nmnh.si.edu/paleo/blast/joides_article.htm

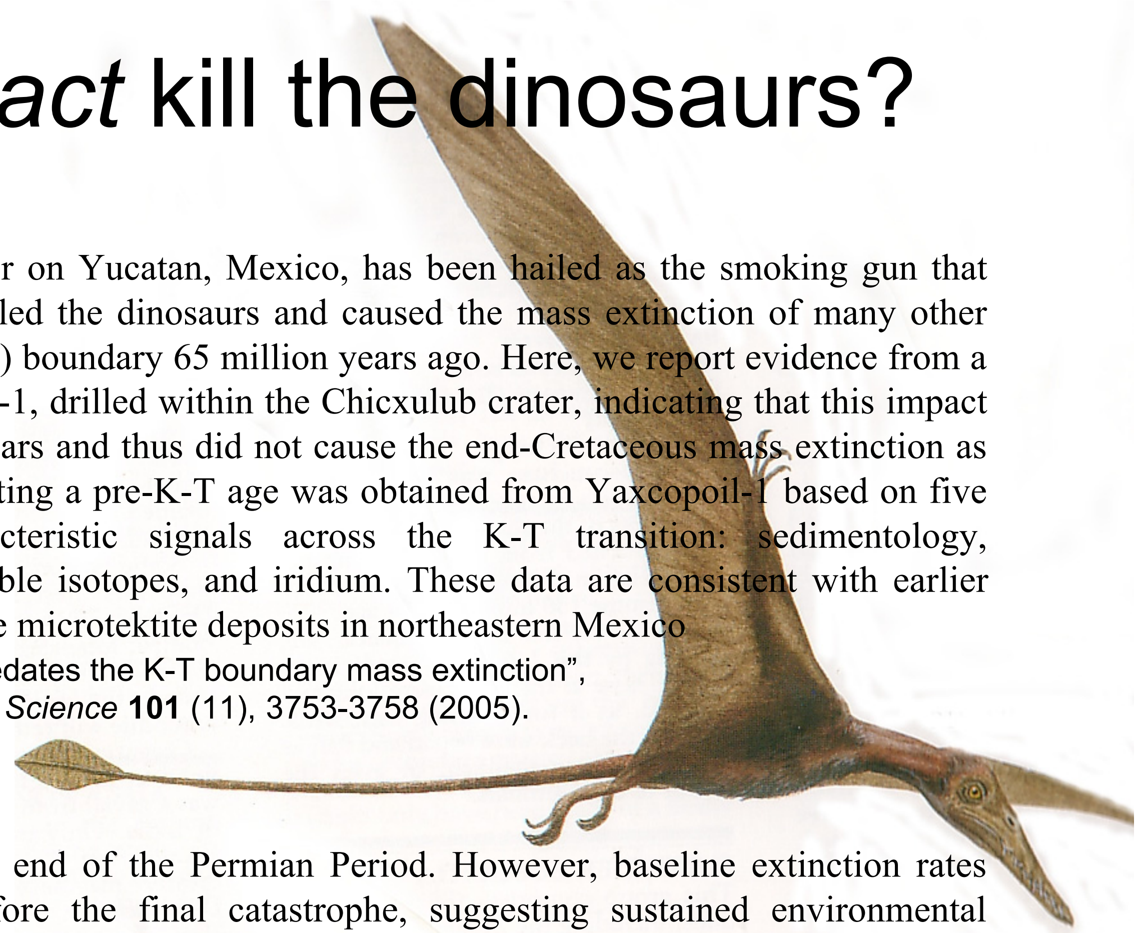
We have shown how the great glacial deposits in Neoproterozoic rocks world-wide and the strata adjacent to them point to an extraordinary type of climatic event, a “snowball” Earth followed by a briefer but equally noxious ultra-warm “greenhouse” world.

Paul F. Hoffman & Daniel P. Schrag, “The Snowball Earth” (1999); http://www-eps.harvard.edu/people/faculty/hoffman/snowball_paper.html

People have argued that if the Earth had ever been a solid white “snowball”, as evidence suggests, too much sunlight would then be reflected back into space and the Earth would never warm up again. However, they did not anticipate that the Earth migrates closer to the Sun in a regular oscillatory pattern of the semimajor axis over tens of millions of years.

* Joint Oceanographic Institutions for Deep Earth Sampling

Didn’t an *impact* kill the dinosaurs?



Since the early l990s the Chicxulub crater on Yucatan, Mexico, has been hailed as the smoking gun that proves the hypothesis that an asteroid killed the dinosaurs and caused the mass extinction of many other organisms at the Cretaceous-Tertiary (K-T) boundary 65 million years ago. Here, we report evidence from a previously uninvestigated core, Yaxcopoil-1, drilled within the Chicxulub crater, indicating that this impact predated the K-T boundary by 300,000 years and thus did not cause the end-Cretaceous mass extinction as commonly believed. The evidence supporting a pre-K-T age was obtained from Yaxcopoil-1 based on five independent proxies, each with characteristic signals across the K-T transition: sedimentology, biostratigraphy, magneto-stratigraphy, stable isotopes, and iridium. These data are consistent with earlier evidence for a late Maastrichtian age of the microtektite deposits in northeastern Mexico

Gerta Keller *et al.*, “Chicxulub impact predates the K-T boundary mass extinction”, *Proceedings of the National Academy of Science* **101** (11), 3753-3758 (2005).

A catastrophic extinction occurred at the end of the Permian Period. However, baseline extinction rates appear to have been elevated even before the final catastrophe, suggesting sustained environmental degradation. For terrestrial vertebrates during the Late Permian, the combination of a drop in atmospheric oxygen plus climate warming would have induced hypoxic stress and consequently compressed altitudinal ranges to near sea level. Our simulations suggest that the magnitude of altitudinal compression would have forced extinctions by reducing habitat diversity, fragmenting and isolating populations, and inducing a species-area effect. It also might have delayed ecosystem recovery after the mass extinction.

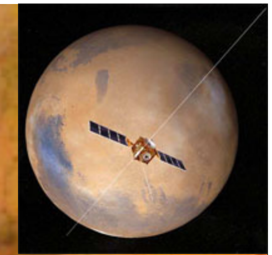
Raymond B. Huey & Peter D. Ward, “Hypoxia, Global Warming, and Terrestrial Late Permian Extinctions”, *Science* **308**, 398-401 (2005).

Dinosaur images, courtesy Two Guys Fossils and the U.S. National Park Service (top-left).

This Mars Express Spacecraft image of Reull Vallis strongly suggests the flow of water in a prior epoch.

Mars – a warmer wetter planet

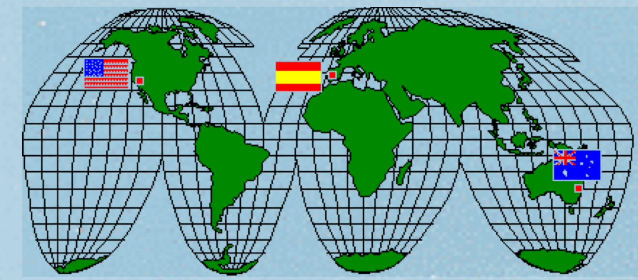
Jeffrey S. Kargel, *Mars – A Warmer, Wetter Planet*, (Springer, London, 2004).



Mars Express

The simplest explanation for how Mars could have been much warmer in the past is that it was closer to the Sun in the past.There is ample evidence of cyclical long-term climate change on Earth with a period on the order of 100 million years. It is reasonably certain that the identical physical phenomenon is responsible for the massive historical climate change experienced by both planets, which for the Earth we know is cyclical. It is likely that Jupiter's inbound migration has strongly influenced Mars' ephemeris.

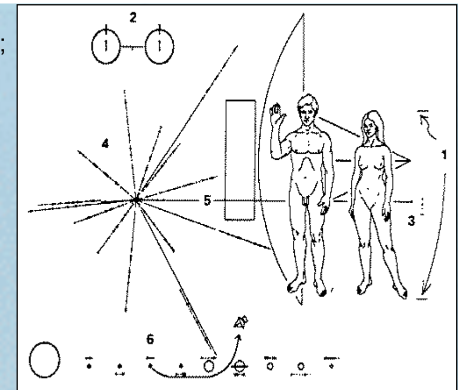
Jeffrey S. Kargel, now at the Astrogeology Branch of the United States Geological Survey in Flagstaff, Arizona, has long proposed that Mars has experienced climate change of similar inexplicable magnitude to Earth, having been a warmer wetter planet in the past in contrast to the presently observed harsh dry cold. A host of new evidence provided by the Spirit and Opportunity Mars rovers discussed in a large collection of articles in the 3 December 2004 issue of the journal *Science* strongly supports this interpretation of Martian geologic features. These data compliment supporting images provided by the Mars Global Surveyor and European Space Agency (ESA) Mars Express spacecraft discussed in another large collection of articles in the 11 March 2005 issue of *Science*.



Global DSN locations & 70*m* dish antenna (background)

Pioneer-10

Greeting from Earth; a message aboard the Pioneer-10 & 11



The Pioneer-10 spacecraft, launched in the early 1970s, was the first space probe sent to the outer planets, destined to follow a hyperbolic escape trajectory tangential to the galactic gravitational gradient, taking it out of the Solar System. Pioneer-10 lived well beyond its expected lifetime and generated useful data into the late 1990s. Its last, very faint contact occurred on 23 January 2002. Its extended data set for the purpose of very precise measurements in celestial mechanics experiments spans 3 January 1987 to 22 July 1998 over which its approximate heliocentric Ecliptic coordinates changed from [range 40 AU, longitude 71°, latitude 3°] to [range 70 AU, longitude 76°, latitude 3°]. Single-axis spin stabilization and its great distance from the Sun, which allowed for a minimum number of external disturbances in the form of maneuvers to reorient the spacecraft antenna towards the Earth, allowed for precision acceleration estimates from Doppler data on the order of 10^{-7} cm/s^2. This is about 1 part in 10 billion of the acceleration experienced on the surface of the Earth; the Pioneer-10 spacecraft was unprecedented in its sensitivity as a detector of Solar System modeling errors and remains unsurpassed in this achievement.

The Pioneer Navigation Team and their extended support infrastructure at the NASA Ames Research Center, the Jet Propulsion Laboratory (JPL), the Aerospace Corporation and Astrodynamic Sciences in Los Angeles, Los Alamos National Laboratory in New Mexico and other facilities have had decades to devote to the data acquisition and analysis of Pioneer-10 and other spacecraft telemetry and to exhaustively rule out any and all sources of systematic error. They report an apparent unmodeled acceleration of the Pioneer-10 spacecraft towards the Sun (the direction opposite to the outbound radial velocity of the spacecraft) on the order of 10^{-7} cm/s^2 that could not be explained by any known physical phenomenon. According to the Doppler data, the spacecraft was receding from the Sun at a rate very slightly less than modeled by exceedingly precise and comprehensive calculations. The possibility of a systematic drift in referenced atomic clocks was ruled out. In effect, what has been observed is an unexplained energy loss of the spacecraft relative to the Sun. This apparent long-term effect, which was not explained, let alone modeled quantitatively, was accompanied by even more intriguing phenomena.

The Doppler frequency data exhibits an annual periodicity approximated by a damped sinusoid with a systematic variation on a time scale of approximately 3 months. The 3-month time scale reflects the following: At conjunction (when the Sun is between the Earth and the spacecraft) the apparent anomalous acceleration of the isolated annual term is at its peak redshift value and initiates a decline in magnitude. Approximately 6 months after conjunction, when the Sun and the spacecraft are in opposition (opposite sides of the Earth) the annual effect attains its local minimum value. The effect then initiates a return to a new peak value at conjunction 6 months later and repeats the cycle. This annual periodicity in the Doppler residuals is superimposed on a 'high-frequency' sinusoidal effect with a period approximately equal to the Earth's inertial sidereal rotation period of $23^h56^m04.1^s$ relative to the distant outbound spacecraft. In summary, the observed anomalous Doppler data is essentially a 'low resolution' sinusoid with an annual period superimposed on a 'high resolution' sinusoid with a diurnal period, with the signal exhibiting a linear Doppler blueshift. The amplitude of the diurnal effect at about 1×10^{-6} cm/s^2 is more than an order of magnitude greater than the long term effect. When examining the data, it is important to note the non-standard opposite sign convention for JPL Doppler data, (positive for an outbound spacecraft) which is not always used consistently and which can thus cause some confusion.

The ephemeris programs employed by the Pioneer Navigation Team must use equations for point-mass relativistic gravitational accelerations. These will, of course, be based on the Schwarzschild metric. There is no doubt that what the Pioneer Navigation Team observed was the *GTR* effect. The following slide provides a graphical description of the observed effect in this context. The "Pioneer Anomaly" is a reflection of the deficiency in Einstein's gravitational model that has been described herein, which is incorporated as a small but critical error in celestial navigation and analysis software.

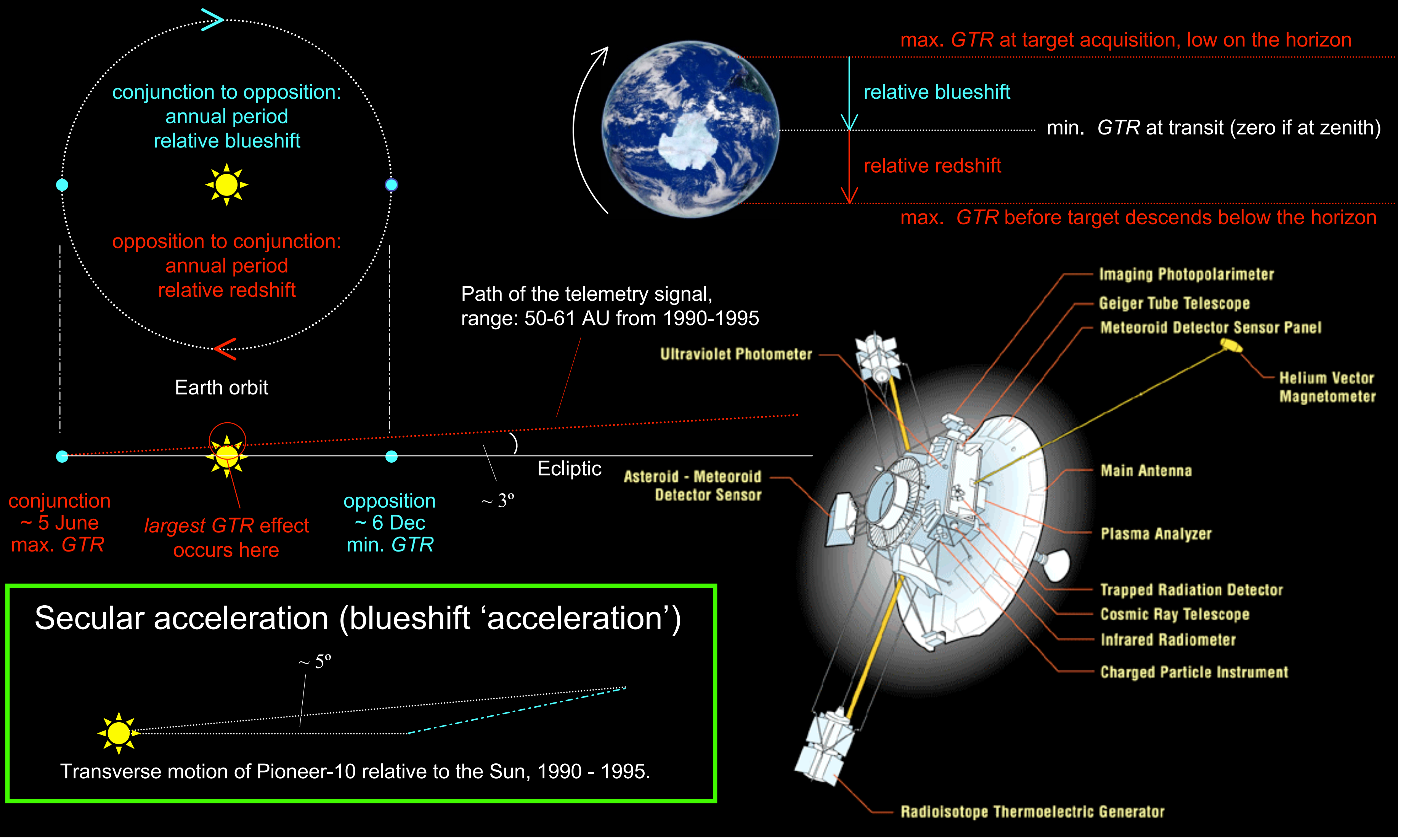
John D. Anderson *et al.,* "Study of the anomalous acceleration of Pioneer-10 and 11", *Physical Review D* **65**, 082004 (2002); arXiv: gr-qc/0104064.

Continued…

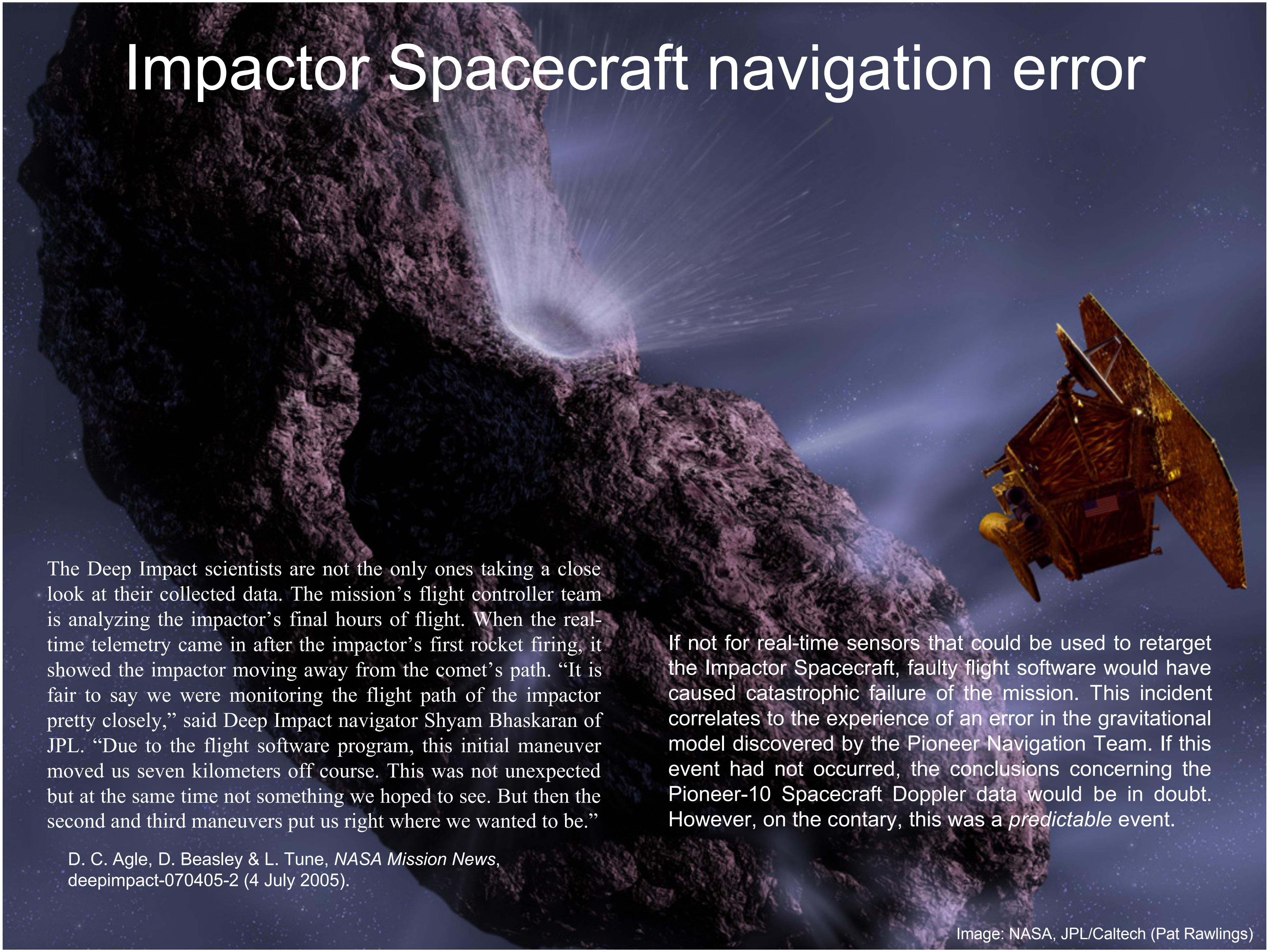
Pioneer-10 *GTR* anomalies

Annual term Doppler anomaly
(‘low-frequency’ sinusoid)

Diurnal term Doppler anomaly
(‘high-frequency’ sinusoid)



Impactor Spacecraft navigation error



The Deep Impact scientists are not the only ones taking a close look at their collected data. The mission's flight controller team is analyzing the impactor's final hours of flight. When the real-time telemetry came in after the impactor's first rocket firing, it showed the impactor moving away from the comet's path. "It is fair to say we were monitoring the flight path of the impactor pretty closely," said Deep Impact navigator Shyam Bhaskaran of JPL. "Due to the flight software program, this initial maneuver moved us seven kilometers off course. This was not unexpected but at the same time not something we hoped to see. But then the second and third maneuvers put us right where we wanted to be."

D. C. Agle, D. Beasley & L. Tune, *NASA Mission News*, deepimpact-070405-2 (4 July 2005).

If not for real-time sensors that could be used to retarget the Impactor Spacecraft, faulty flight software would have caused catastrophic failure of the mission. This incident correlates to the experience of an error in the gravitational model discovered by the Pioneer Navigation Team. If this event had not occurred, the conclusions concerning the Pioneer-10 Spacecraft Doppler data would be in doubt. However, on the contary, this was a *predictable* event.

Image: NASA, JPL/Caltech (Pat Rawlings)

Gravity Probe B

See einstein.stanford.edu

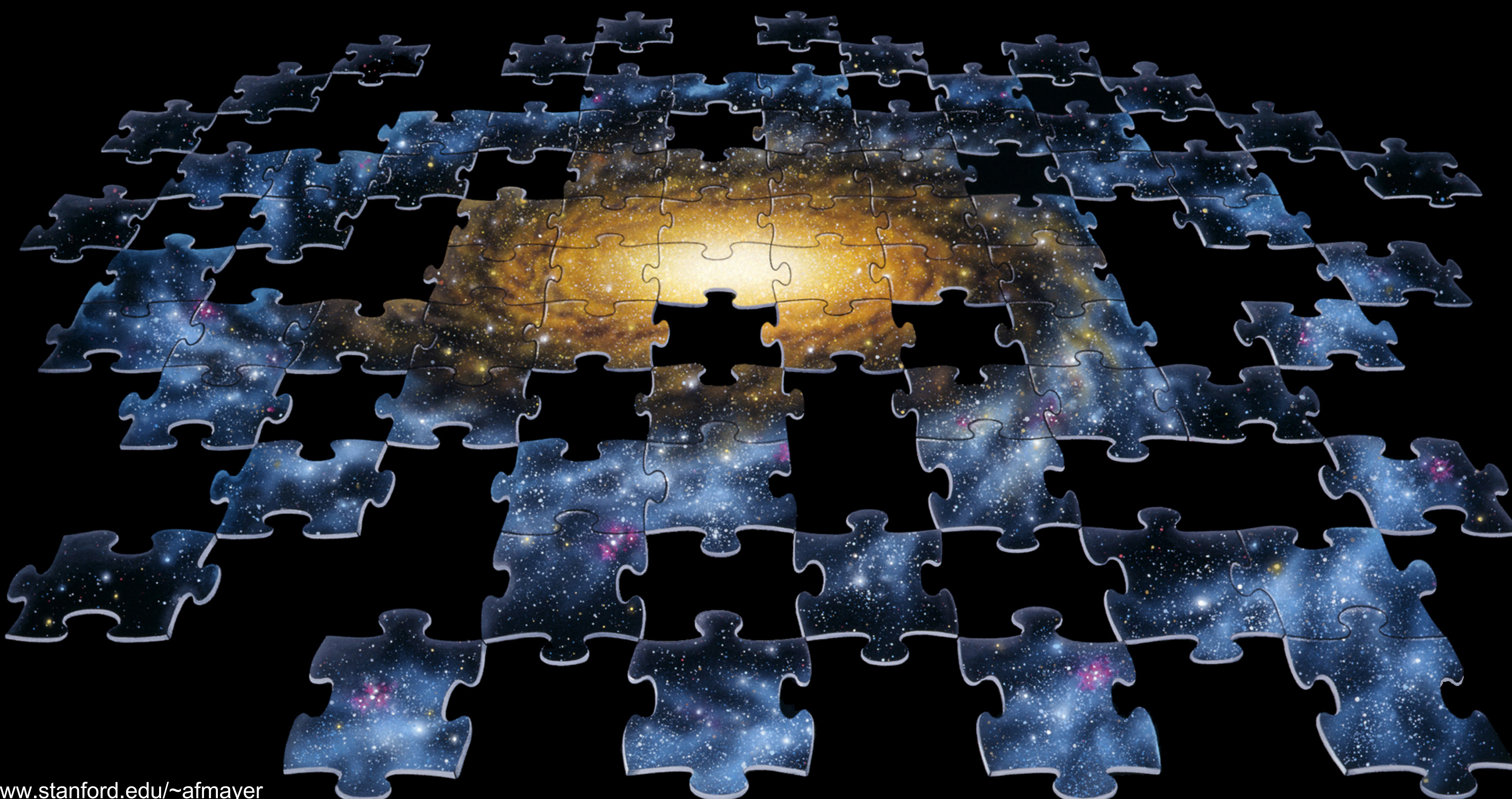
Gravity Probe B was launched in April of 2004 and completed the data-gathering phase of the mission in October of 2005. Its mission is to measure two very subtle predicted effects of general relativity, the geodetic effect and the Lense-Thirring effect, using a set of the most sensitive gyroscopes ever constructed. The geodetic effect is a theoretical general phenomenon applicable to any gyroscope moving through a curved spacetime for which the spin vector is not perpendicular to the orbital plane. Because spacetime is not ‘curved’ in the way Einstein thought it was, there is no geodetic effect to measure. However, the *GTR* effect will have made the GP-B satellite orbit decay quite rapidly as has been observed for geodetic satellites,. This should have introduced a very noticeable effect on the gyroscopes. It is possible that the unanticipated *GTR* effect may have overwhelmed any ability to measure the exceedingly small Lense-Thirring or ‘frame-dragging’ effect.

The author (A. Mayer) has never been privy to any GP-B results.

Ronald J. Adler & Alexander S. Silbergleit, “A General Treatment of Orbiting Gyroscope Precession”, *International Journal of Theoretical Phyics* **39**, 1291-1316 (2000); arXiv: gr-qc/9909054.

This amendment to general relativity also implies a change to the Big-Bang cosmological model. This is discussed in Lecture 2: *The Many Directions of Time*.

THANK YOU.



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