A New Gravitational Effect

Understanding Anomalies in the Global Positioning System (GPS)

The Introductory Lecture
17 slides : ~10 minutes

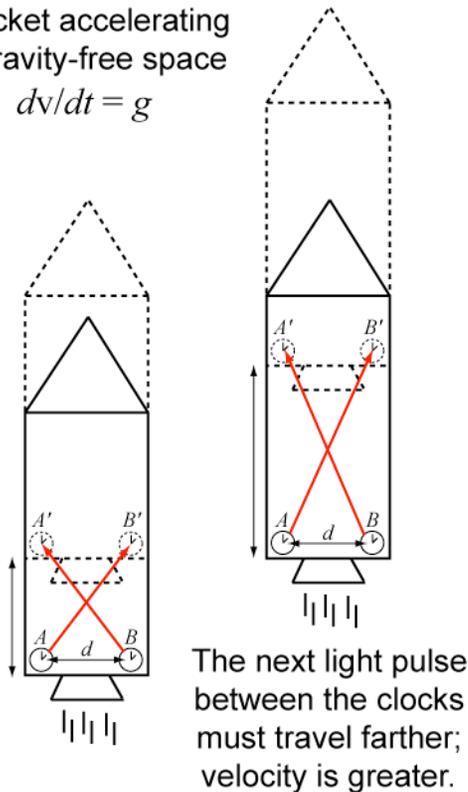1 February 2006
Rev. 6 February

The Problem: GPS Anomalies

"The principle [sic] 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. Furthermore, other anomalies have been found in Air Force monitor station data that are not understood at present."

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.

Relativistic Transverse Redshift

a rocket accelerating
in gravity-free space
$$dv/dt = g$$

The next light pulse
between the clocks
must travel farther;
velocity is greater.

Motivated by Feynman:
See *The Feynman Lectures on Physics –
Volume II*, pp. 42-8 to 42-11.
(It just never occurred to anyone to do it *this* way.)

- Two identical clocks A and B, both at the tail of an accelerating rocket, 'tick' with pulses of light.

- The speed of light traveling between the clocks is not affected by the motion of the rocket.

- According to an inertial observer, each new pulse travels a greater distance to reach the other clock.

- The incurred additional time delay for the arrival of each new light pulse implies that the arrival rate of pulses is less than their emission rate.

- Therefore, according to accelerated observers at each ideal clock, the rate of the other ideal clock is less than the rate of the local ideal clock.

- The frequency of arriving light must be less than the frequency of the light that was emitted by the other clock; there is a redshift between the clocks.

Simplistic Quantitative Analysis

a rocket accelerating
in gravity-free space
$dv/dt = g$

A d B

$\Delta v = gd/c$

- The time for light to travel between the clocks as measured inside the rocket is $\Delta t = d/c$.

- In that time, the acceleration of the rocket g will have caused a $\Delta v = gd/c$ between the clock receiving a light pulse and the clock that emitted the pulse, *at the time the pulse was emitted*.

- Accordingly, there will be a transverse Doppler shift between the clock that emitted the pulse and the clock that received the pulse.

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

- The magnitude of the effect is not measurable in the laboratory for available values of g and d.

The Equivalence Principle

the same rocket at rest
in a gravitational field
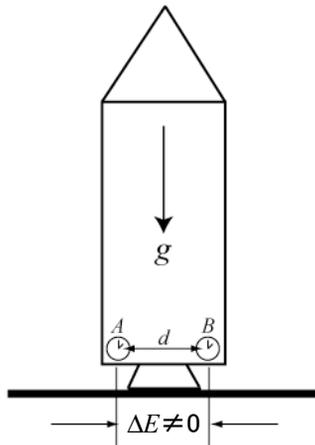
Yes, a totally 'absurd' idea, but quantum theory is 'absurd' and yet observations prove it to be correct. Are there observations consistent with this idea? After all, that is all that matters…

- The results of an experiment in an inertially accelerated reference frame are identical to those in a gravitationally accelerated reference frame.

- Although ideal clocks A and B are at relative rest and at identical gravitational potential, the clocks are not synchronous according to first principles.

- The symmetric relativistic time dilation between the clocks implies that light exchanged between the clocks will incur a redshift (energy loss).

- According to the principles of relativity, there is no such thing as a gravitational equipotential surface in the classical sense.

- An ideal gravitational 'equipotential surface' does not imply that no work is done for ideal frictionless translation over the surface, if relativistic effects are taken into consideration.

Implied Unmodeled Effect

Both signal paths have components transverse to the gravitational gradient.
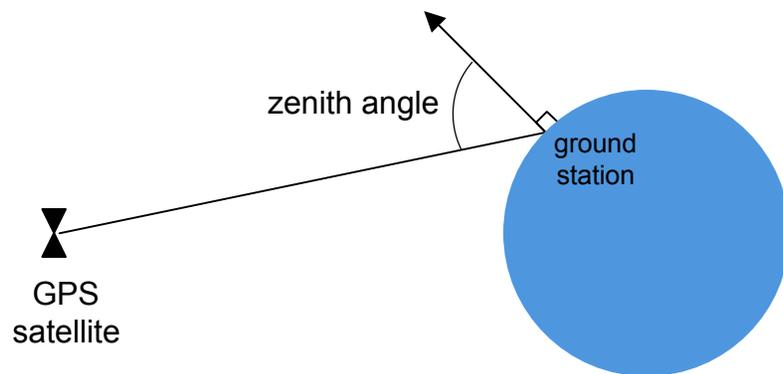
redshift of GPS satellite signal proportional to zenith angle of satellite
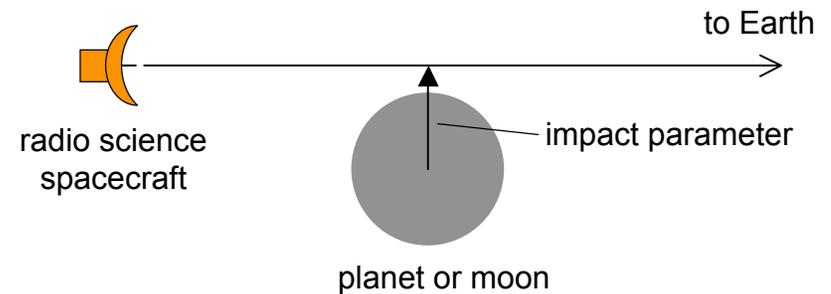
redshift of signal inversely proportional to gravitational 'impact parameter'.

The Schwarzschild Metric

- The Schwarzschild space-time metric is an exact solution to the Einstein field equations, assuming a static and symmetric gravitational field around a point-like mass in vacuum.

- The metric does not model the phenomenon of a gravitational transverse redshift.

- There is a dissimilarity between the physical implications of first principles and the model used by GPS (GR) that must be resolved.

GR – general relativity

Implications: GPS

- GPS satellite signals must incur a small but measurable *unmodeled* time delay that is proportional to the zenith angle of the space vehicle (SV) relative to the ground station.

- Accuracy of GPS is good enough to observe the small modeling error, but as the cause of the anomaly is *dynamic*, it would be virtually impossible to determine its nature without some kind of theoretical guidance.

Expected Residual Pattern

- GPS SVs have an orbital period that is half of 1 sidereal day so that they cover the identical ground track every 24 hours.

- The gravitational transverse redshift (*GTR*) effect is a maximum when the SV is at the horizon and a minimum at transit, relative to a USAF GPS monitoring station on the ground.

- The *GTR* effect would result in a semidiurnal triangular wave pattern of pseudo-range (PR) residuals, correlated with the topocentric rise and fall of each SV.

Observed Residuals: GPS

satellite 32-p
meters vs days
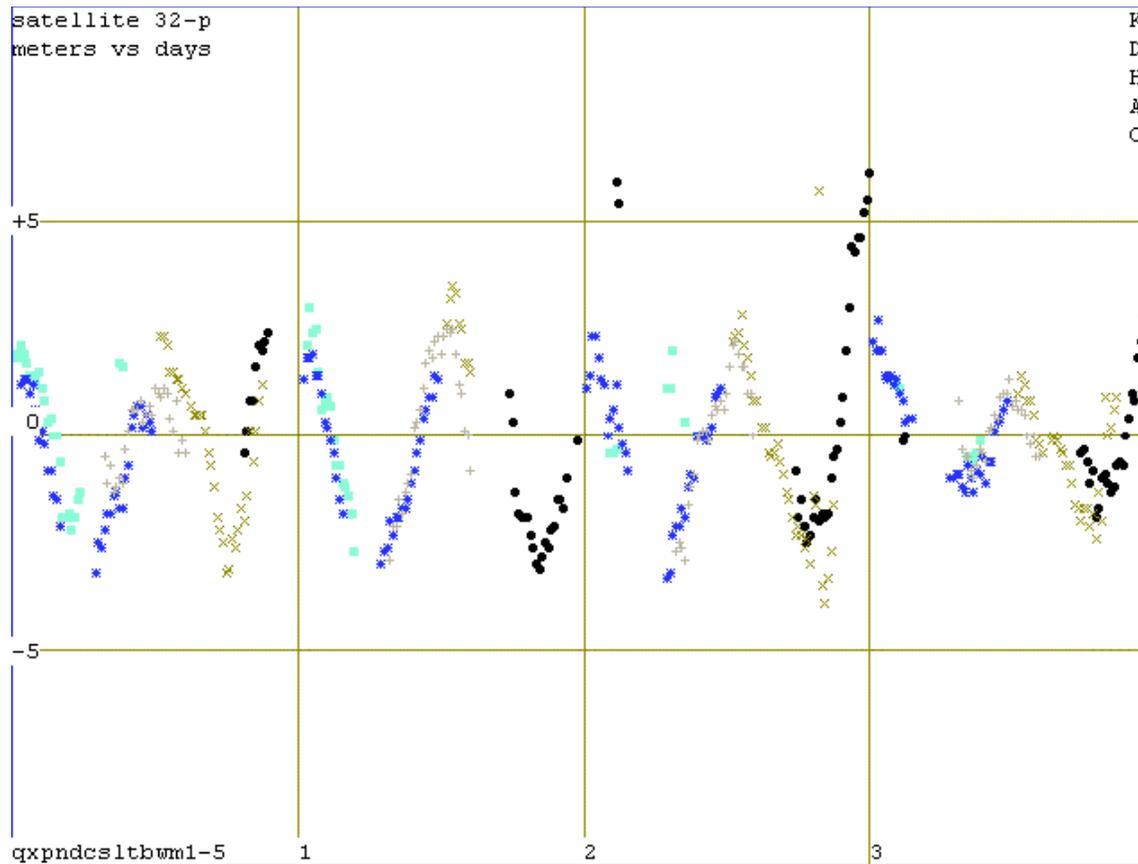
—quoted from the paper—
Superimposed on true data noise and smaller systematic trends is a "saw-tooth" effect in the residuals for individual satellites. This effect is most pronounced in Figure 5, where a roughly 12-hour periodicity is likewise evident. Thinking that the 1-2 meters amplitude was too large to be due to errors in the orbits, we considered various exotic mechanisms, such as variations in clock behavior due to high-speed motions through Earth's magnetic fields, which would reverse polarity in each satellite every six hours as the satellites changed magnetic hemispheres. However, none of the mechanisms considered had good predictive behavior over the entire set of data.

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

Figure 5. *Pseudo-range residuals for all monitor stations for satellite SV 32.*
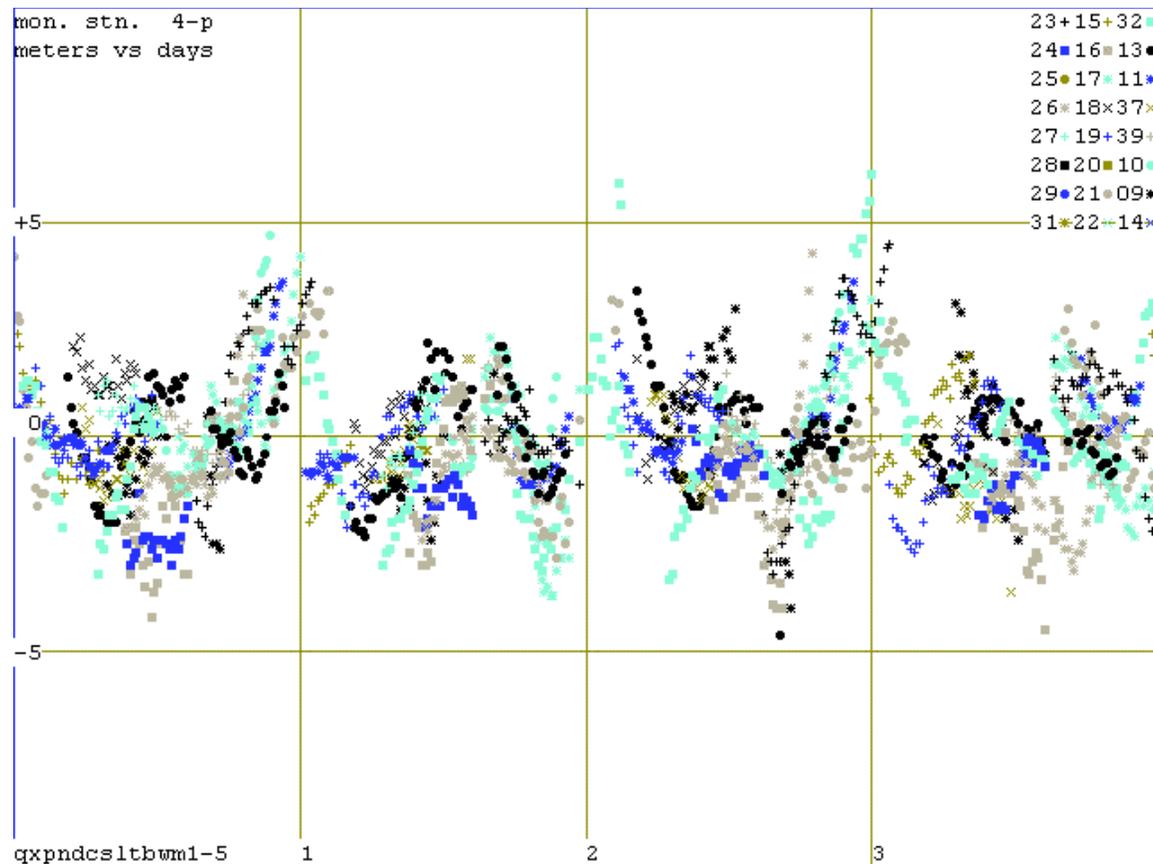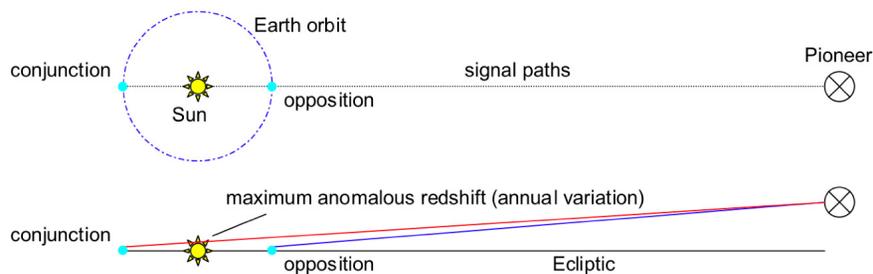
Observed Residuals: GPS

Figure 3. *Pseudo-range residuals for all satellites at Diego Garcia.*

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

The Pioneer Anomaly

If the GPS anomalies are caused by a gravitational transverse redshift, then the same phenomenon must similarly affect the radio Doppler signal from a remote Solar System spacecraft. The triangular wave pattern of *apparent* acceleration residuals would be diurnal rather than semidiurnal because the remote spacecraft would rise and fall in the sky only once per day. Also, if that spacecraft were near to the Ecliptic, then the diurnal variation of the signal would be superimpose an annual sinusoidal variation of the signal due to motion of the Earth around the Sun. The unmodeled annual modulation of the radio Doppler signal *mimicking* acceleration would have peaks and valleys at conjunction and opposition, corresponding to the changing path of the radio Doppler signal relative to the Sun.

ANDERSON, LAING, LAU, LIU, NIETO, AND TURYSHEV

CHASMP Doppler Residuals For Interval III
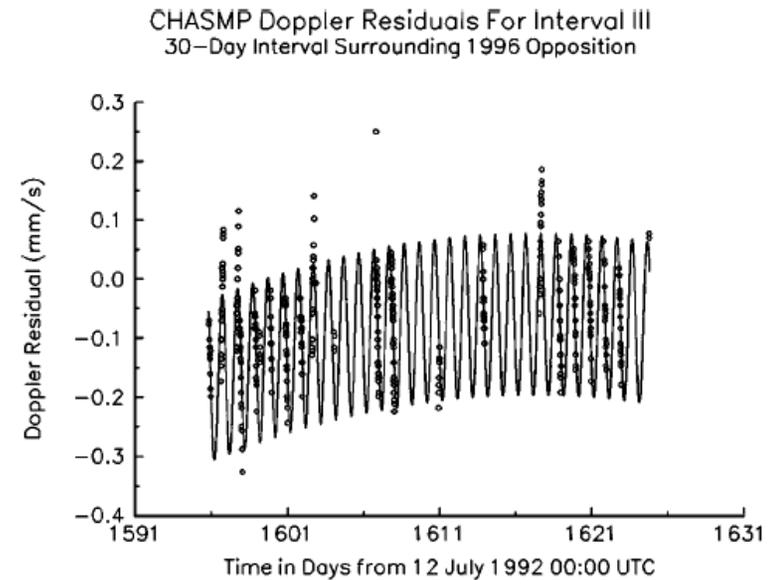30—Day Interval Surrounding 1996 Opposition

FIG. 18. CHASMP acceleration residuals from 23 November 1996 to 23 December 1996. A clear modeling error is represented by the solid diurnal curve. (An annual term maximum is also seen as a background.)

John D. Anderson *et al.*, "Study of the anomalous acceleration of Pioneer-10 and 11",
Phys. Rev. D **65**,082004 (2002); http://arxiv.org/abs/gr-qc/0104064

Implications: Radio Science

- A spacecraft radio signal returned to Earth with a path adjacent to a moon or planet must incur an unmodeled redshift that could be interpreted as an atmospheric effect, unless there is no atmosphere.

- The observed effect on a radio Doppler signal implies a sudden acceleration of the spacecraft away from the Earth (redshift) followed by an acceleration toward the Earth (blueshift back to normal).

- A possible interpretation of the observable is that unlikely "mass anomalies" have created anisotropies in the gravitational field, however one would expect to also see obvious geographical features or dynamical behavior (wobble) associated with such anomalies.
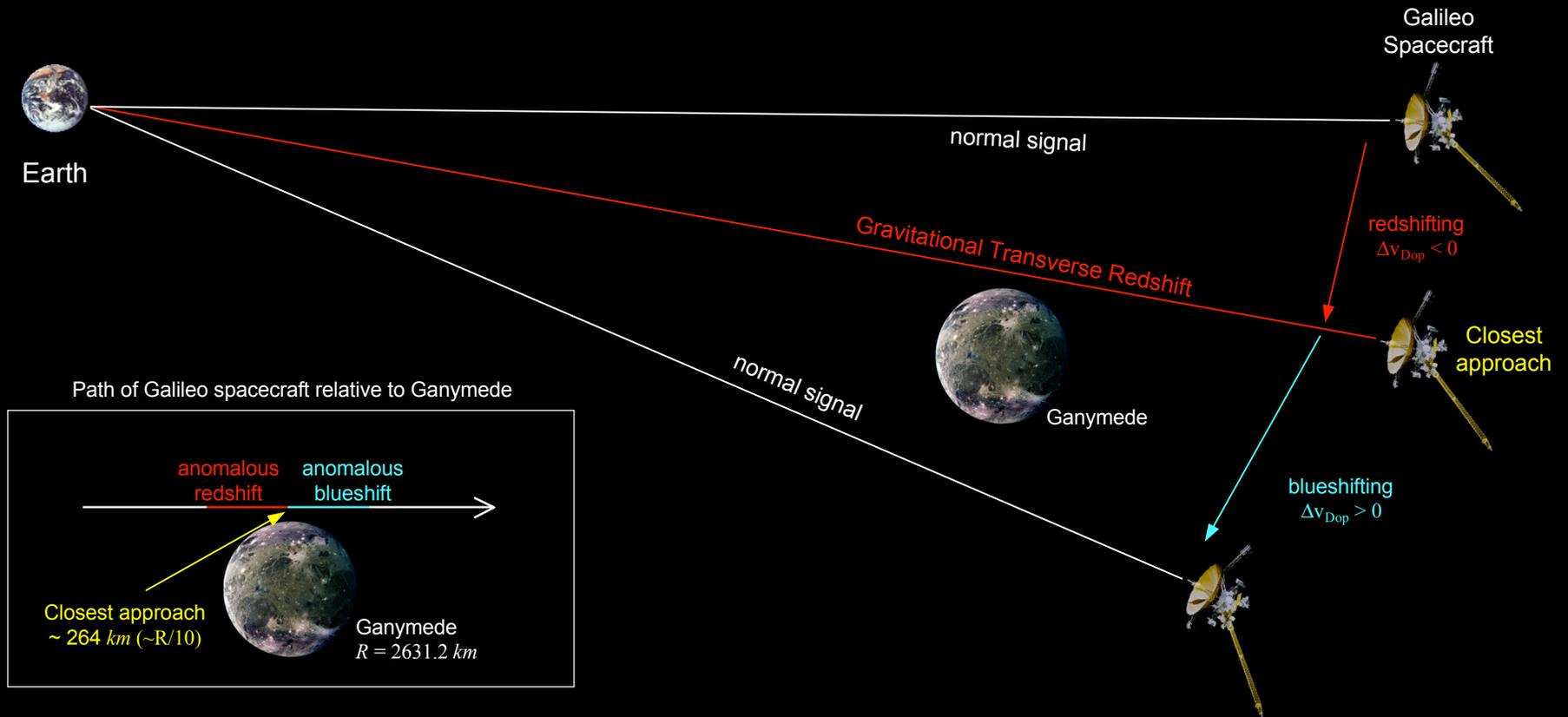
Evidence: Ganymede Flyby

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.

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

Implications: Starlight

- The majority of a star's observed photons are emitted from regions nearer the limb, so their initial path to the telescope will have a component transverse to the star's gravitational gradient.

- A gravitational transverse redshift will result in an unmodeled excess redshift of starlight that is proportional to the star's surface gravity.

- Therefore, the largest anomalous redshift will be measured for compact (high surface gravity) white dwarf stars, a smaller anomaly observed for large bright stars, and the smallest anomaly seen for relatively small stars like our Sun.

- Interpreted as an Einstein (gravitational radial) redshift, the observed significant excess redshift of white dwarf stars will imply a mass that is too large for a white dwarf star to form according to astrophysical considerations.
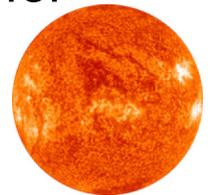
Evidence: Excess Redshifts

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 $10\text{–}15\ km\ s^{-1}$ (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", *ApJ* **313**, 750-756 (1987).

The K-Effect is well known. Large, bright Class B stars (such as Rigel in Orion) typically exhibit an apparent excess redshift of $K \approx 4km/s$. Interpreted as a Doppler shift, the K-Effect makes the inference that larger, hotter stars have the improbable singular quality of a higher recession velocity from the Sun than smaller, cooler stars.

After correction for the gravitational redshift and for all the known relative motions between sun and observer, the average residual redshift [of the sun] is 7 mÅ and could be from 5 to 12 mÅ for some individual reference lines. This corresponds in terms of velocity to an equivalent Doppler-Fizeau shift on the whole spectrum of about $1\ km\ s^{-1}$ away from the observer.

D. Samain, "Is the ultraviolet spectrum of the quiet sun redshifted?", *A&A* **244**, 217-227 (1991).

Additional Information

- The dissimilarity between predictions based on first principles and those based on the Einstein field equations suggests an error in the field equations.

- The nature of that error and its greater implications are discussed in two new (January 2006) lectures, available at

www.stanford.edu/~afmayer
www.alexandermayer.com