CGPM

The Unpredictable Rotation of the Earth

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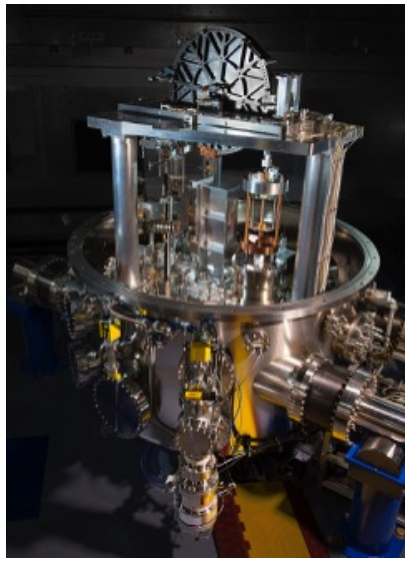
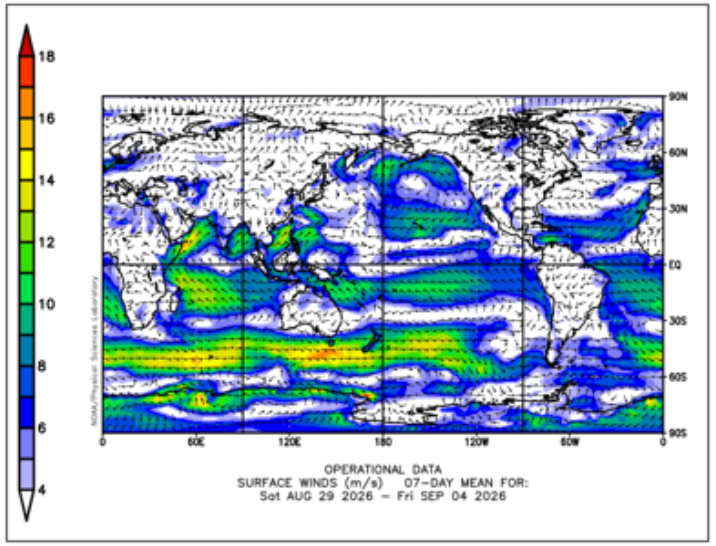
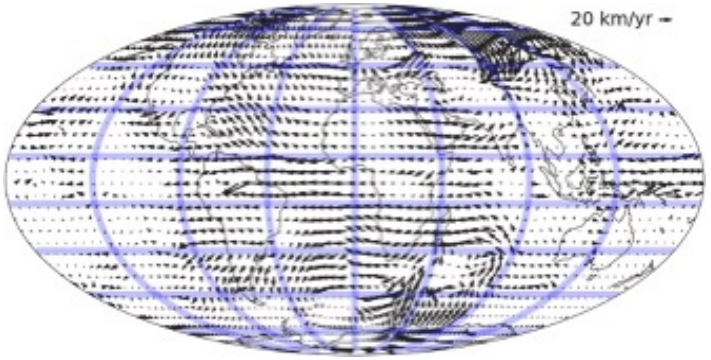
- Metrology is (to me) an **experimental** science which works with controlled situations.





- Geophysics is an **observational** science that studies uncontrollable and complicated processes: earthquakes, weather, the Earth's magnetic field… and its rotation.





Earth Rotation and Time

Until the 1950's these were equivalent: noon (sun overhead) depends on Earth rotation. And the Earth was the master clock--and the best available.

Navigation depended on comparing local noon, **defined by Earth rotation**, to time at longitude 0 degrees: local time at Greenwich (also rotational).



RV Horizon, 1959

From 1972, broadcast time (**UTC**) counted Atomic seconds, with **adjustments as needed** to keep UTC time within 0.9 seconds of **UT1,** a timescale **defined** by Earth rotation.

Adjusting UTC: Leap Seconds, + and -

Earth is **slow**

UT1	UTC
59:58	59:59
59:59	59:60
00:00	00:00

Insert an extra second with an unusual label into a UTC minute.

A **positive leap second**

Earth is **fast**

UT1	UTC
59:58	59:57
59:59	59:58
00:00	00:00

Skip over (extract) the last second from a UTC minute.

A **negative leap second**

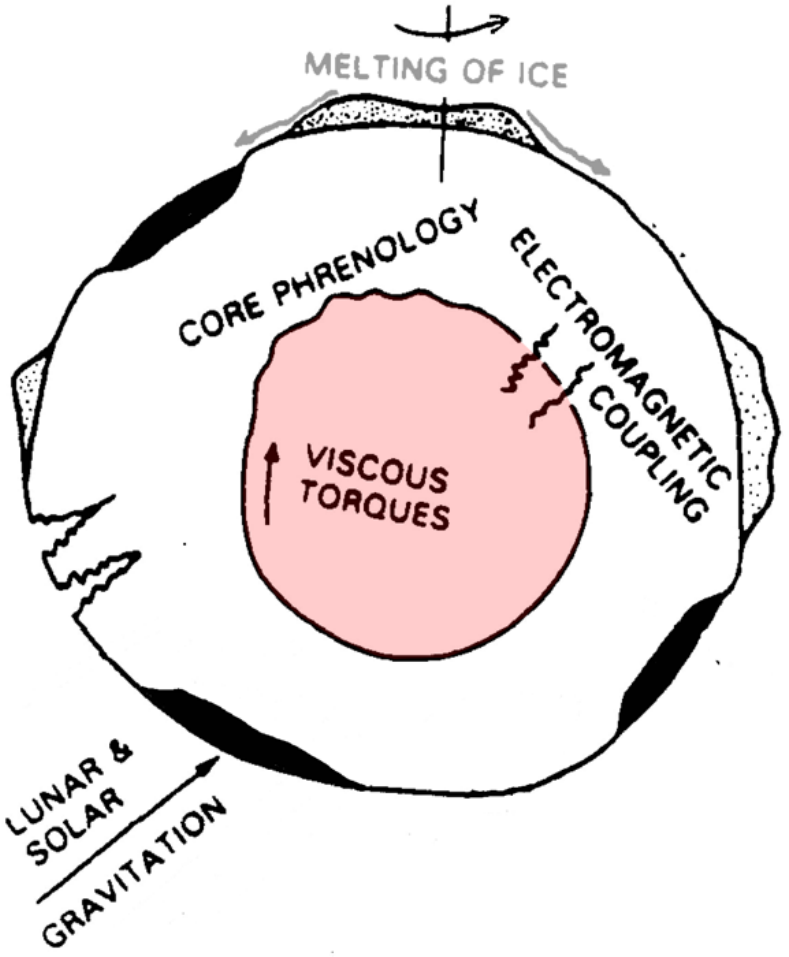
Why Does the Earth's Rotation Rate Vary?

Many kinds of mass motions and applied forces.

These must be **large** and **long-lasting** to matter for 1-second timekeeping.

We can ignore weather, earthquakes, ocean currents.

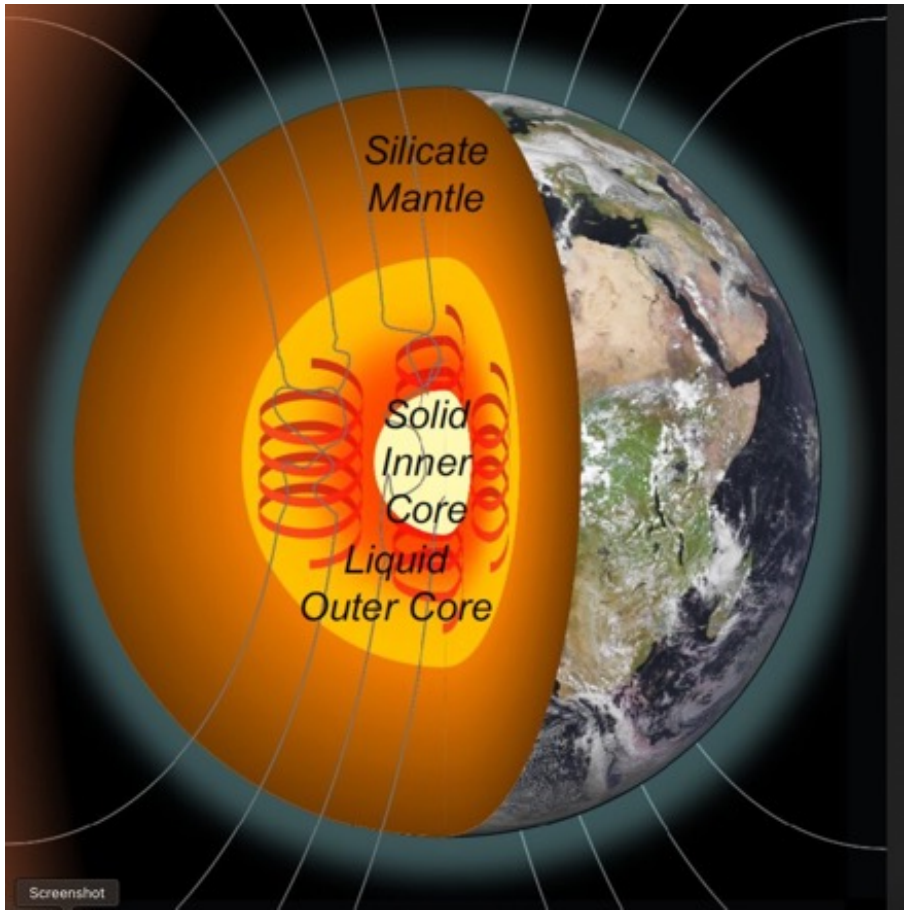
Most important effects: steady slowing of the Earth by **tidal friction,** and **motion in the core.**



What do we know about the Earth's Core?

- Inside the solid crust and mantle
- About the size of Mars and three times as massive
- Liquid (viscosity of water); 5% solid (Inner core)
- Mostly iron/nickel, some lighter elements
- Moving at 10-20 km/yr, turbulent
- Magnetohydrodynamic dynamo produces Earth's magnetic field
- Changes in motion vary the rotation rate of the solid Earth

Only 2900 km away!

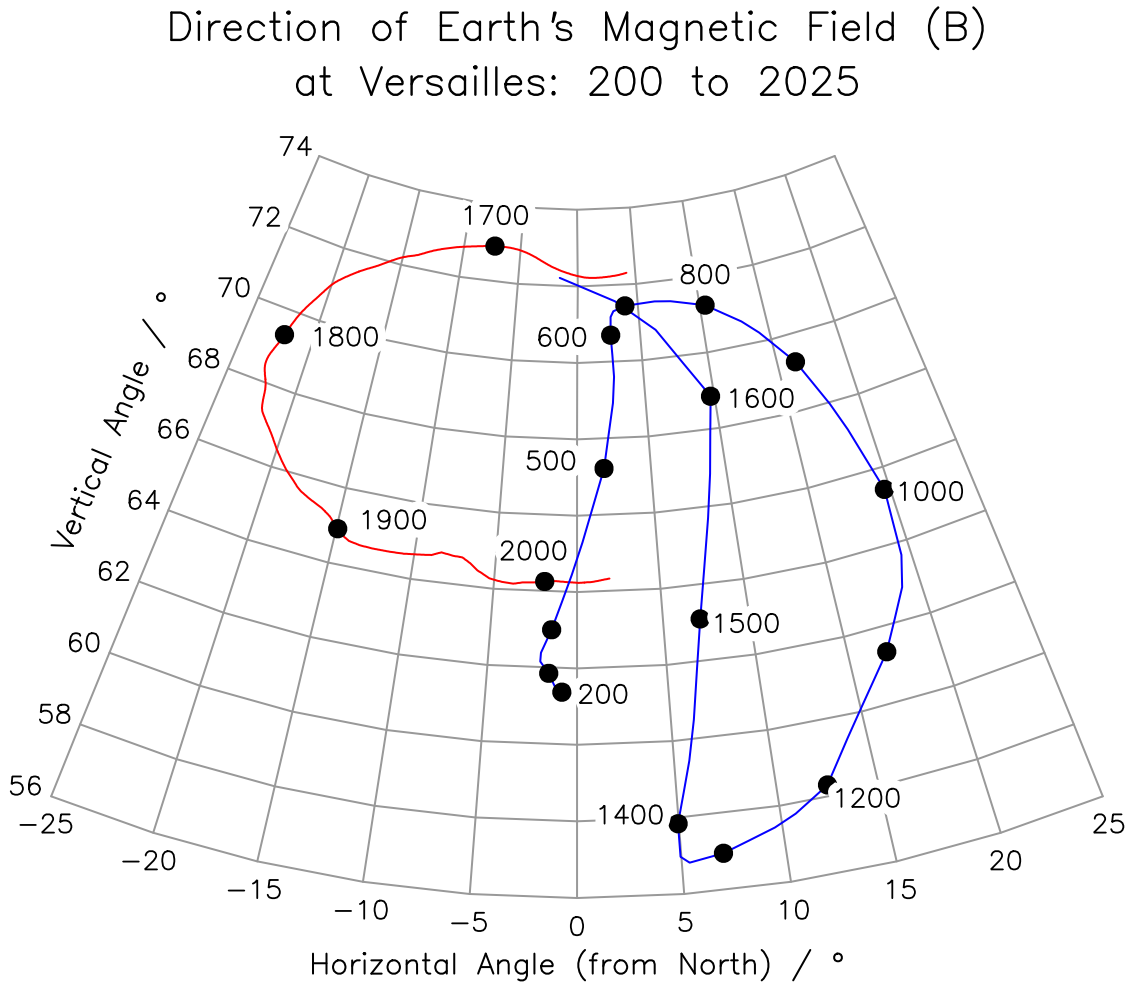


Evidence of Core Motions (I)

At any location, the direction of the Earth's magnetic field changes with time.

Changes over long times can be large—the field can even reverse*.

The field is unpredictable—so the motions in the core are as well.



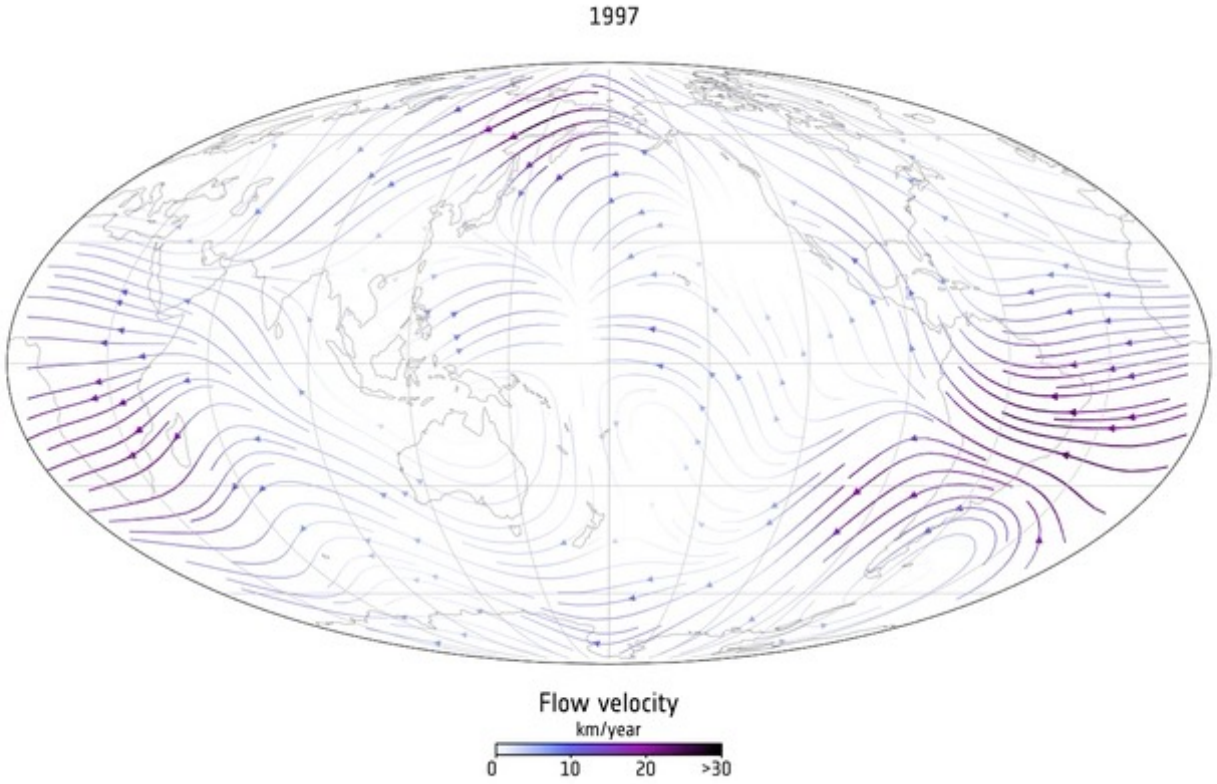
* $10^{5.5}$ $-10^{6.5}$ yr between reversals, sometimes much more

Flow at the Top of the Core: 1997-2025

ESA satellite missions provide global field data after 1997, which can show flow at the top of the core.

In 2017, beneath the Pacific, flow reversed direction.

An irregularity typical of a turbulent, chaotic flow.



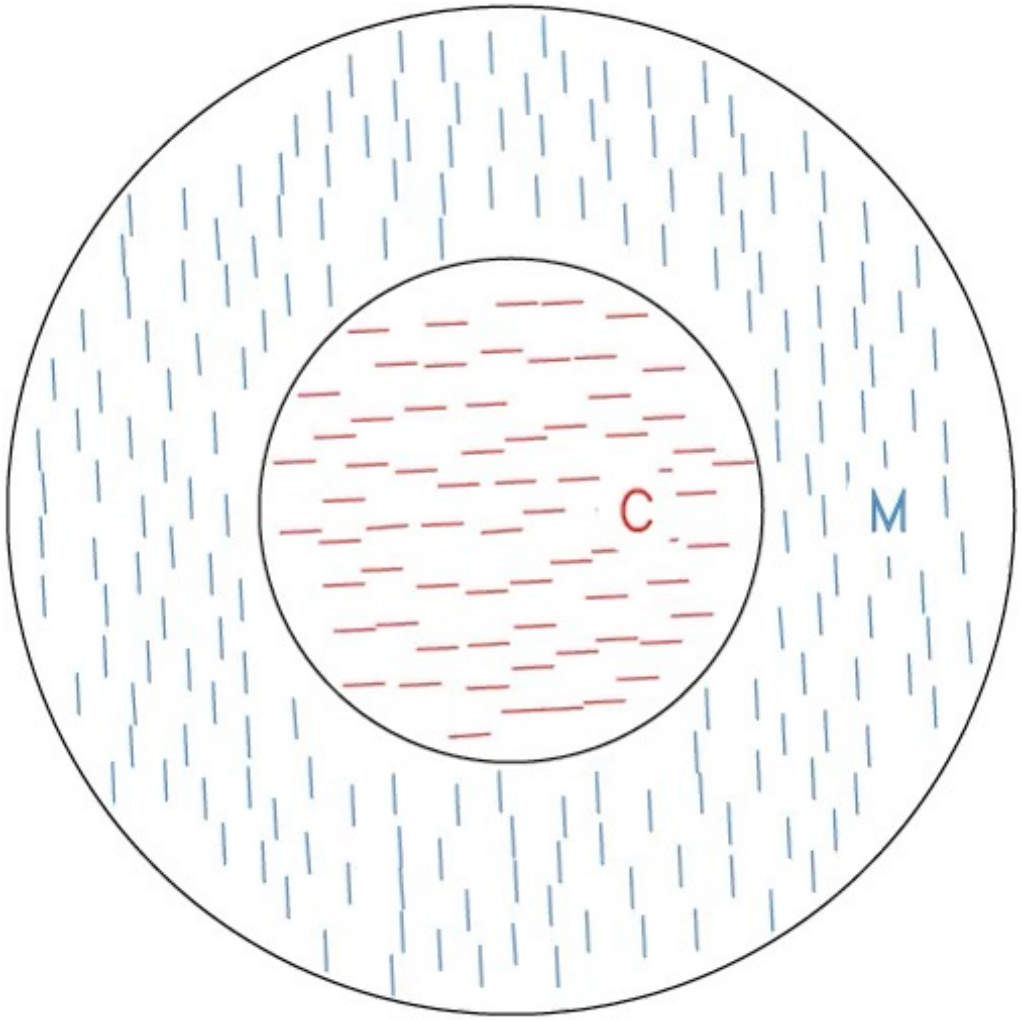
Whaler et al, 202, *Geophysical Research Letters,*
https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2022GL09861
Video from
https://www.esa.int/ESA_Multimedia/Videos/2026/05/Change_in_Earth_s_molten_core_flow_1997_2025

Why does the core affect rotation?

The fluid core can spin at a different rate than the overlying solid Earth (the mantle).

The total amount of spin in Core and Mantle (angular momentum) cannot change.

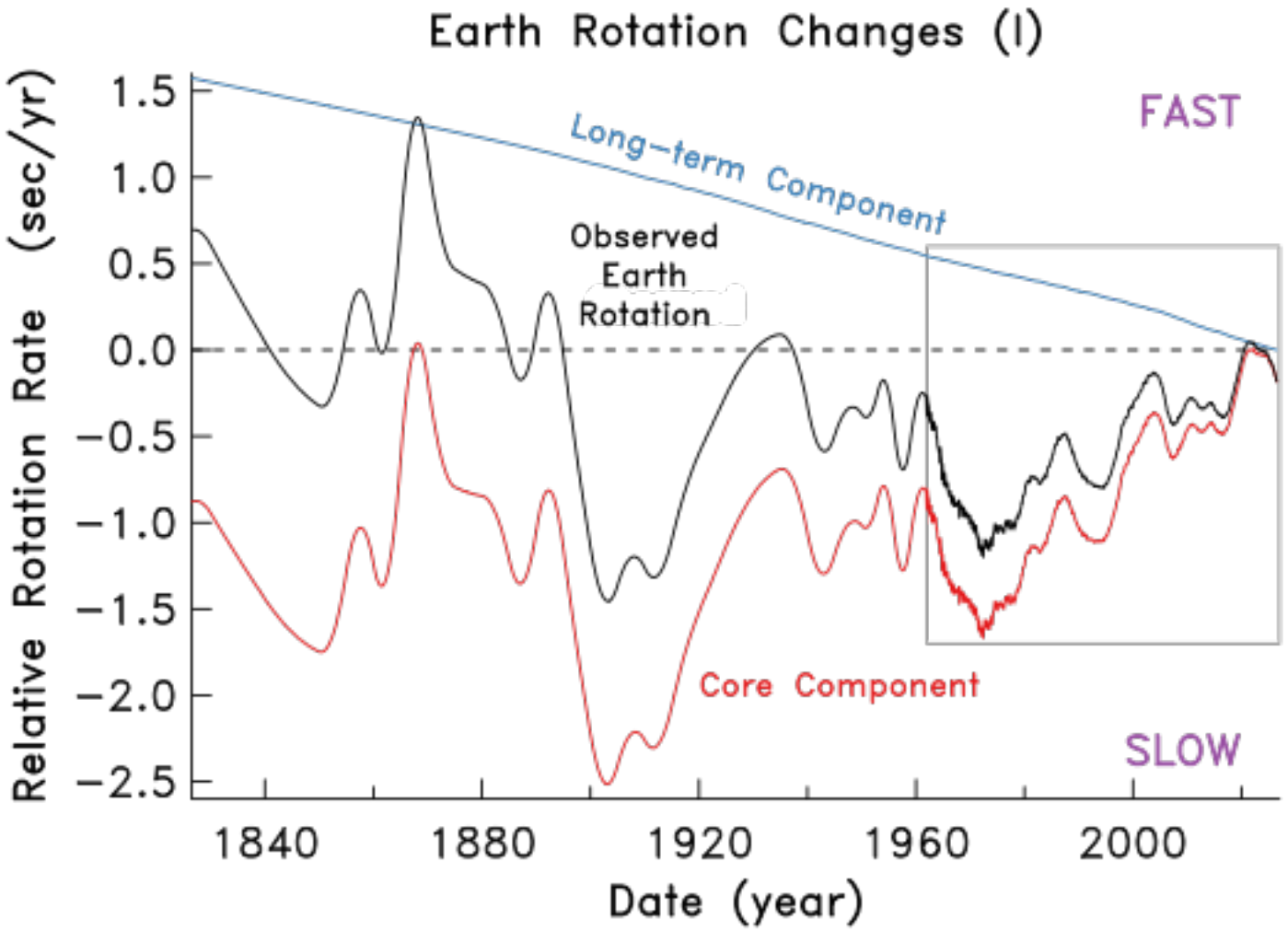
If C speeds up, M has to slow down—or C slows, M goes faster.



Evidence of core motions (II)

In the last 200 years (the span of good data), the **observed rotation** has not varied predictably.

The **predictable part** is much smaller than the **unpredictable random walk behavior** caused by chaotic motion in the core.



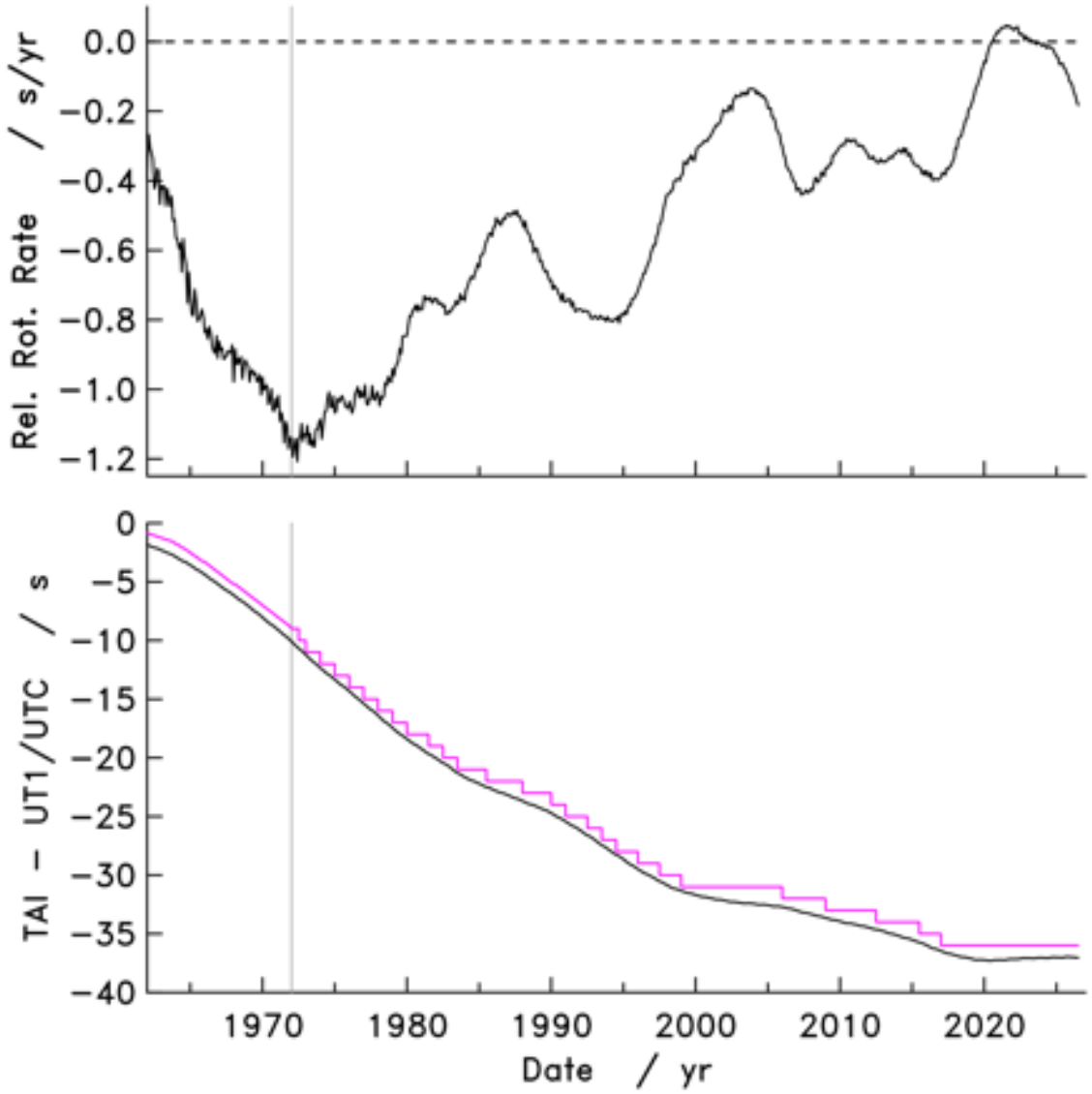
64 Years of Earth Rotation, UT1, and UTC

This animation shows how the Earth's rotation has sped up and slowed down since 1962.

And how this has produced faster and slower changes in UT1

And the irregularity of leap seconds needed to keep UTC matched to UT1

(UTC offset by 1 second for visual clarity)

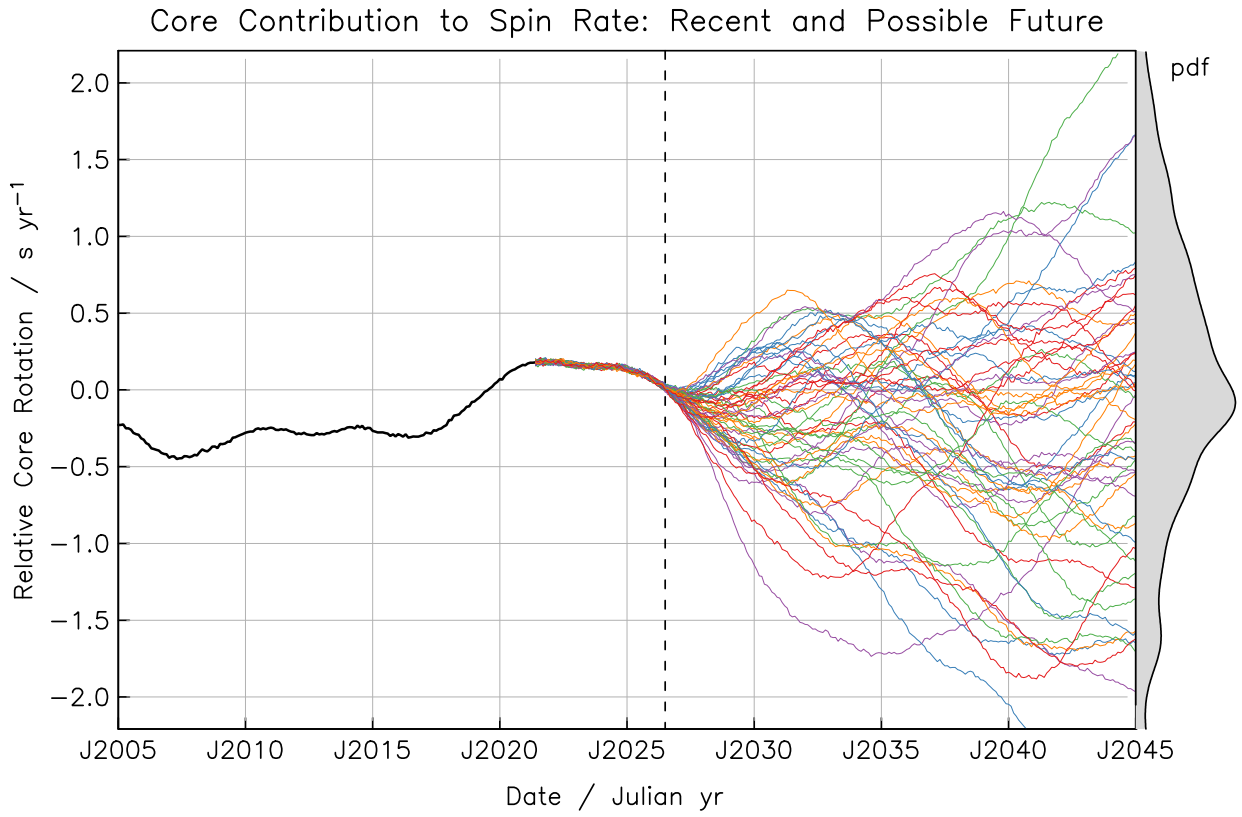


Predicting future rotation

From known statistics of past core behavior (power spectrum)

Use random numbers to find **many possible** future behaviors

[In detail: generate 8000 series of 5000 years each, then find part of each one that matchs the last 5.5 year of data, and take 20 years after that]



D. C. Agnew (2026) The future(s) of UT1: a geophysical discussion. *Metrologia,* **63,** 105010

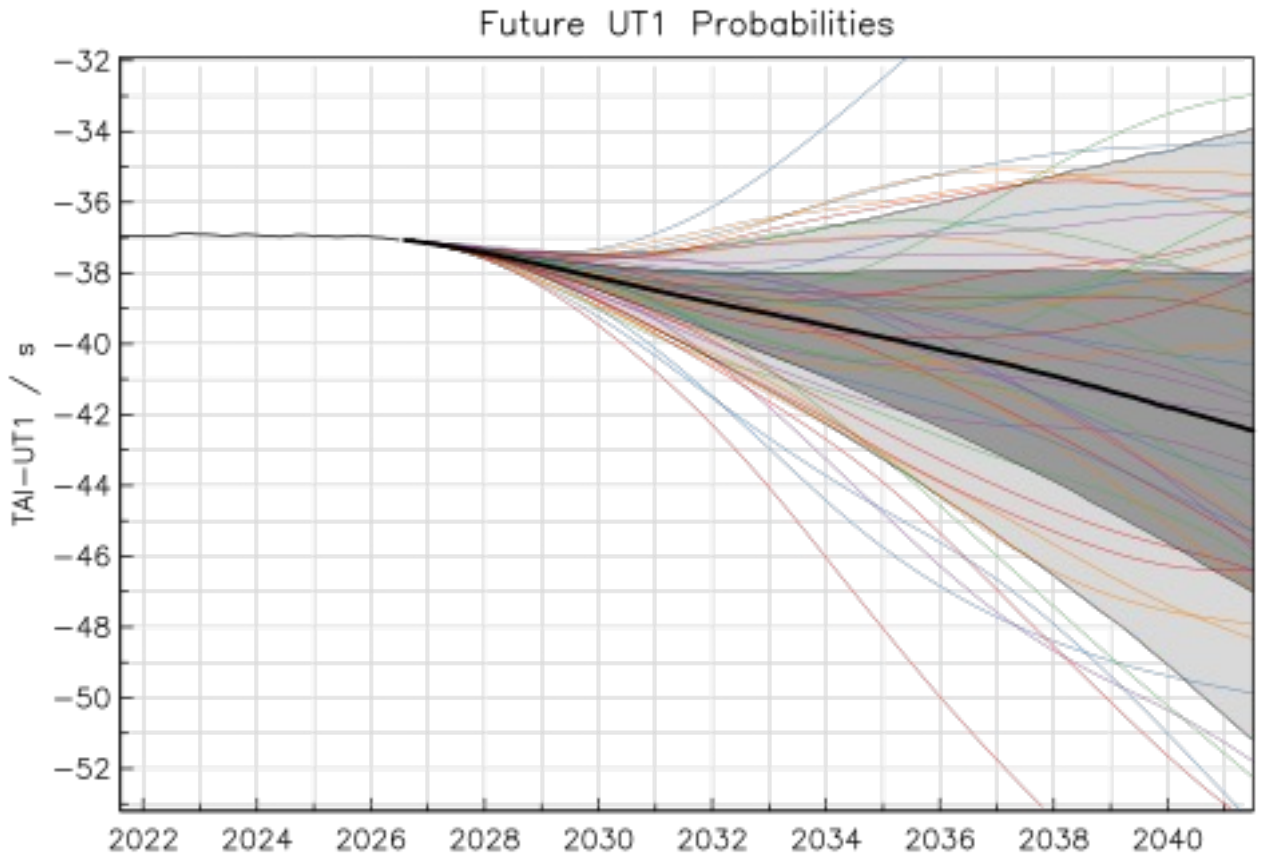
https://iopscience.iop.org/article/10.1088/1681-7575/ae449f

Predicting UT1

For each predicted core behavior, add long-term variation and get predicted UT1

The plot shows a few possible futures, and the statistics (1 and 2 sigma)

From paths, can get probability of leap seconds



Conclusion: Unpredictable Rotation

Motion in the core

dominates changes in rotation for periods from years to centuries

completely dominates what happens to UT1 over a lifetime

and **cannot be predicted**.

So we cannot predict what leap seconds will be needed: but as more than one simulation has shown, both positive and negative have significant chances of happening.

W. Thomsen (Kelvin), 1868

When [clocks] shall be made
two or three hundred times as good as they are now.....
it will not then be necessary to set the clock by the stars,
but we shall test the earth's motion by the clock.