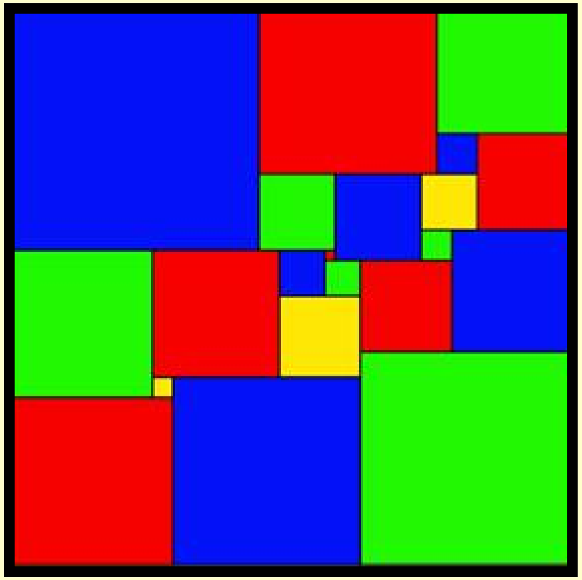
How do we do science?

Brian Williams
MMED
Muizenberg: May 2016



Why science teachers should not be given playground duty.

This is how we teach it

First you learn about numbers.

Then you learn to do experiments.

Then you express the results of your experiments in numbers.

Then your professors say: ‘Go forth and multiply’.

But this is how we do it

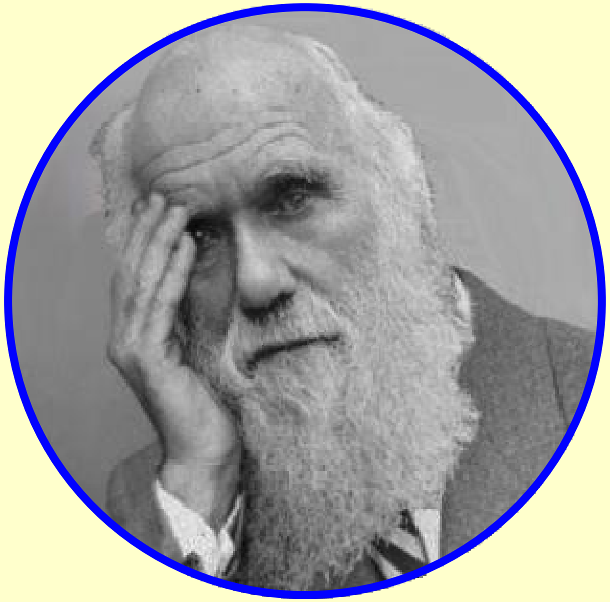
1. Look for interesting patterns. Curiosity!
2. Invent stories to explain them. Theory!
3. Figure out a way to make quantitative predictions. Hypothesis!
4. Work out the consequences of your hypothesis. Modelling!
5. Collect data to test the predictions. Experiment!
6. Start again at 1! Persistence!

Telling stories

Rebecca made clear, by concrete illustrations, by her own self, the two wholly different, wholly separate forms of thought and mind, ‘paradigmatic’ and ‘narrative’
A child follows the Bible before he follows Euclid. Not because the Bible is simpler (the reverse might be said), but because it is cast in a symbolic and narrative mode.

Oliver Sachs ‘Rebecca’ in *The Man Who Mistook his Wife for a Hat* (Pan Books, Gerald Duckworth, London, 1986) p. 174.

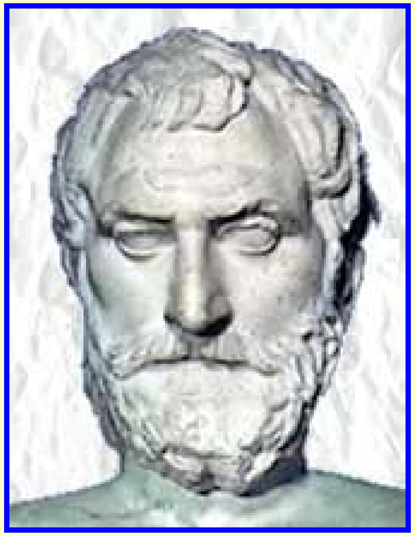
Something to think about



Charles Darwin
1809–1882

If Darwin was right and evolution is about passing on your genes

- Why do we have two sexes?
- Why do we have as many boys as girls?
- Why did sex evolve in the first place?



Anaximander 610 BC–546 BC

Stars over the North Pole

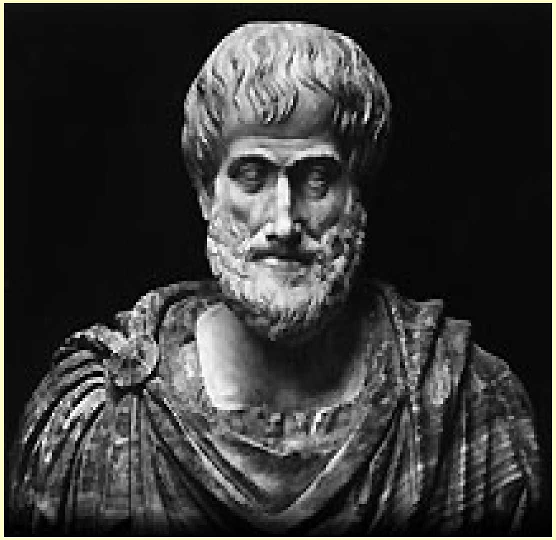
Anaximander: The sun and the moon are in hoops and the stars are in a sphere rotating around the earth with fires outside them. Holes in the hoops and the sphere let out the light.

Lesson 1

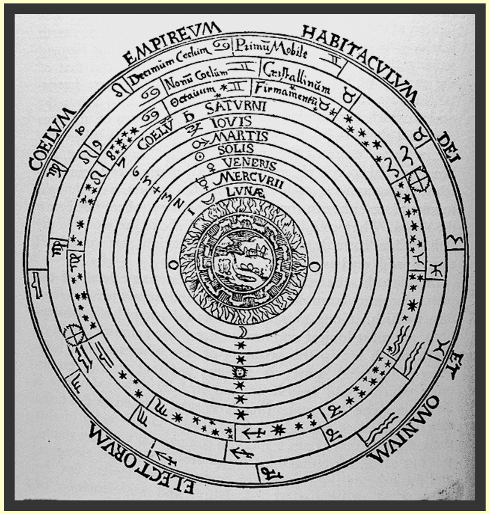
Look for patterns in the world and try to explain them.

The object of all science, whether natural science or psychology, is to co-ordinate our experiences into a logical system.

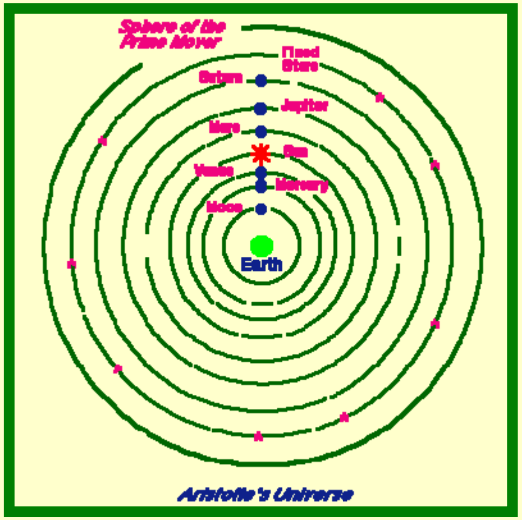
Einstein A. *The Meaning of Relativity* (1922) (Chapman & Hall, London, 1978) p. 1.



Aristotle
384–322 BC



Planets as wanderers



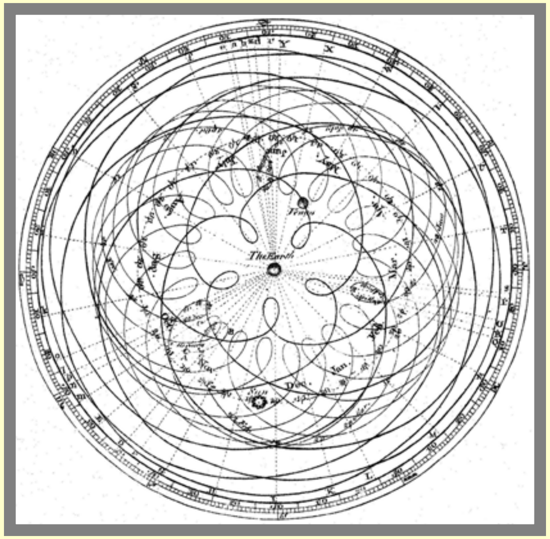
- **Plato to Aristotle:** There are 55 interconnected concentric spheres each attached to the next sphere and to the planets.

Lesson 2

Once you have established a pattern it is the *exceptions* that are interesting.

After a rule is established beyond all doubt, the facts in conformity with it become dull because they no longer teach us anything new. Then it's the exception that becomes important.

Pirsig R.M. *Zen and the Art of Motorcycle Maintenance* (Bantam Books, William Morrow, New York, 1980) p. 238.



Claudius Ptolemy
AD 90–168

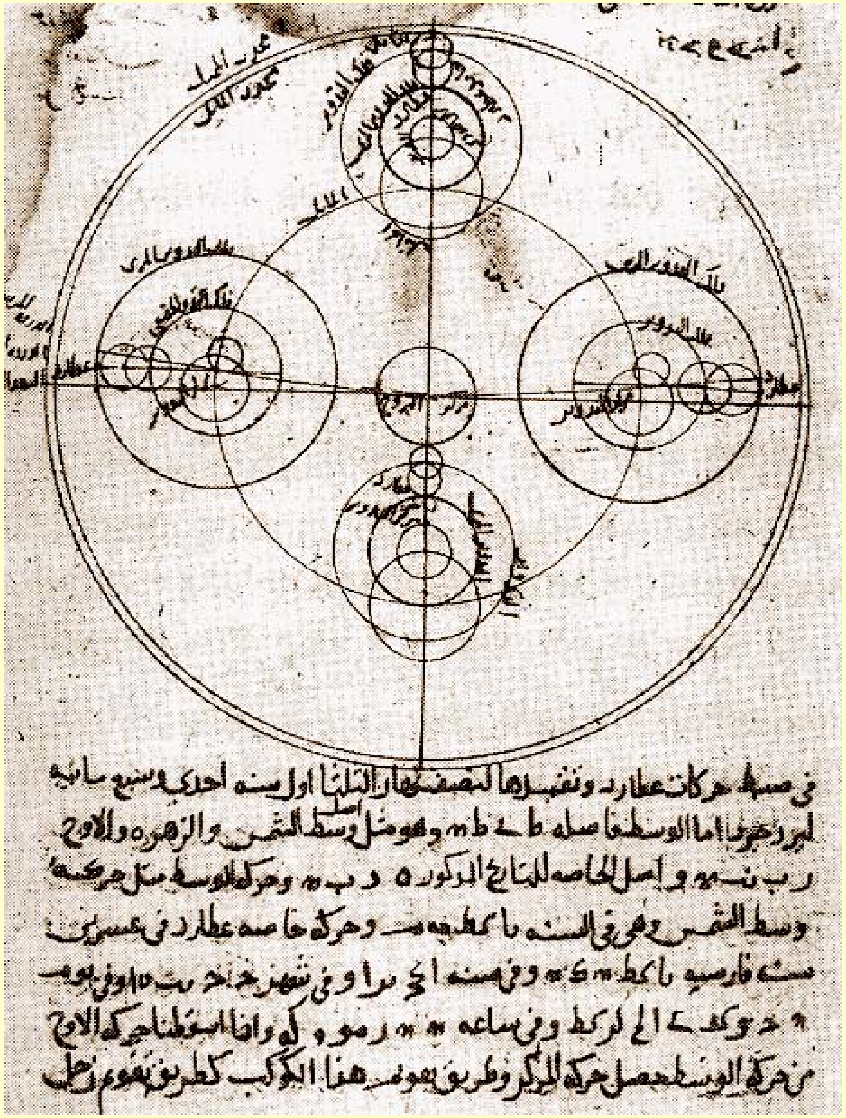
Epicycles

The Antikythera mechanism

Discovered in 1900, off the Greek island of Antikythera, on a ship going to Rome for Julius Caesar.

Ibn al-Shatir (1304–1375)

Model showing the multiplication of Ptolemaic epicycles needed to fit the orbit of mercury



From: *Kitab nihayat as-sul fi tashih al-usul: A Final Inquiry Concerning the Rectification of Planetary Theory*

Lesson 3

Collect data, make a new theory and see if you can predict what is going to happen next!

I don't know of any major theory that has been advanced just on the basis of experiment. The theory always came first The theory [is then used to] make predictions, which then can be tested by observation. If the observations agree with the predictions, that doesn't prove the theory; but the theory survives to make further predictions, which again are tested against observation. If the observations don't agree with the predictions, one abandons the theory.

Stephen Hawking in *Black Holes and Baby Universes* (Bantam Books, Toronto, 1993) pp. 34–35.

Aristarchus (310–ca. 230 BC)

Aristarchus has brought out a book wherein the fixed stars and the Sun remain unmoved, the Earth revolves about the Sun on the circumference of a circle, the Sun lying in the middle of the orbit, and the sphere of the fixed stars, [is] situated about the same centre as the Sun.

Archimedes *The Sand Reckoner*
www.lix.polytechnique.fr/Labo/Ilan.Vardi/sand_reckoner.ps

Tycho Brahe 1546-**1601**

Brahe
The sun and moon go around the earth; everything else goes around the sun.

Johannes Keppler 1571-1630

Keppler/Copernicus
Everything goes around the sun.

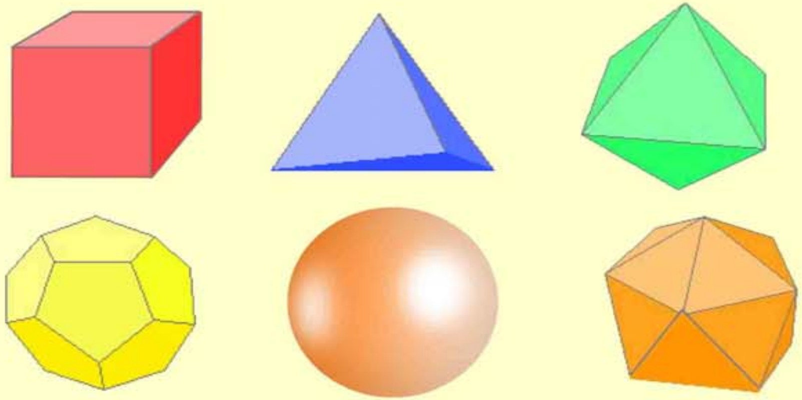
Lesson 4

If it is too complicated try changing your point of view.

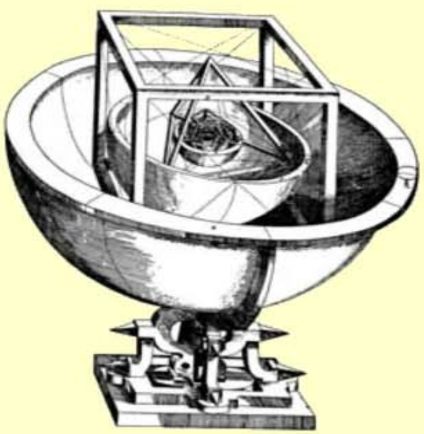
the supreme goal of all theory is to make the basic elements as simple and as few as possible

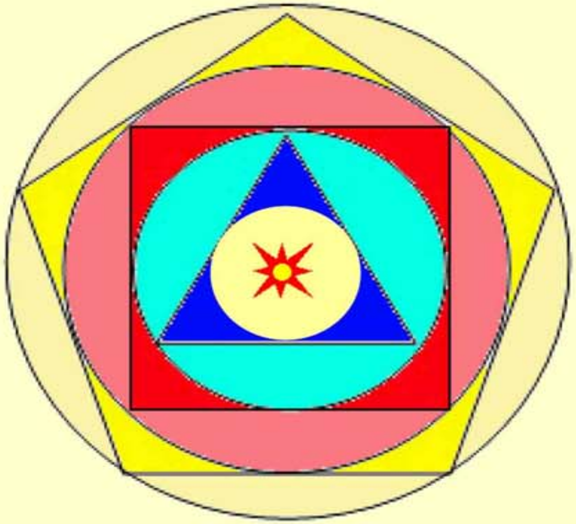
Einstein A, *On the Method of Theoretical Physics* Herbert Spencer Lecture, Oxford, June 1933)

Keppler's challenge



Mercury, Venus, Earth, Mars, Jupiter, Saturn

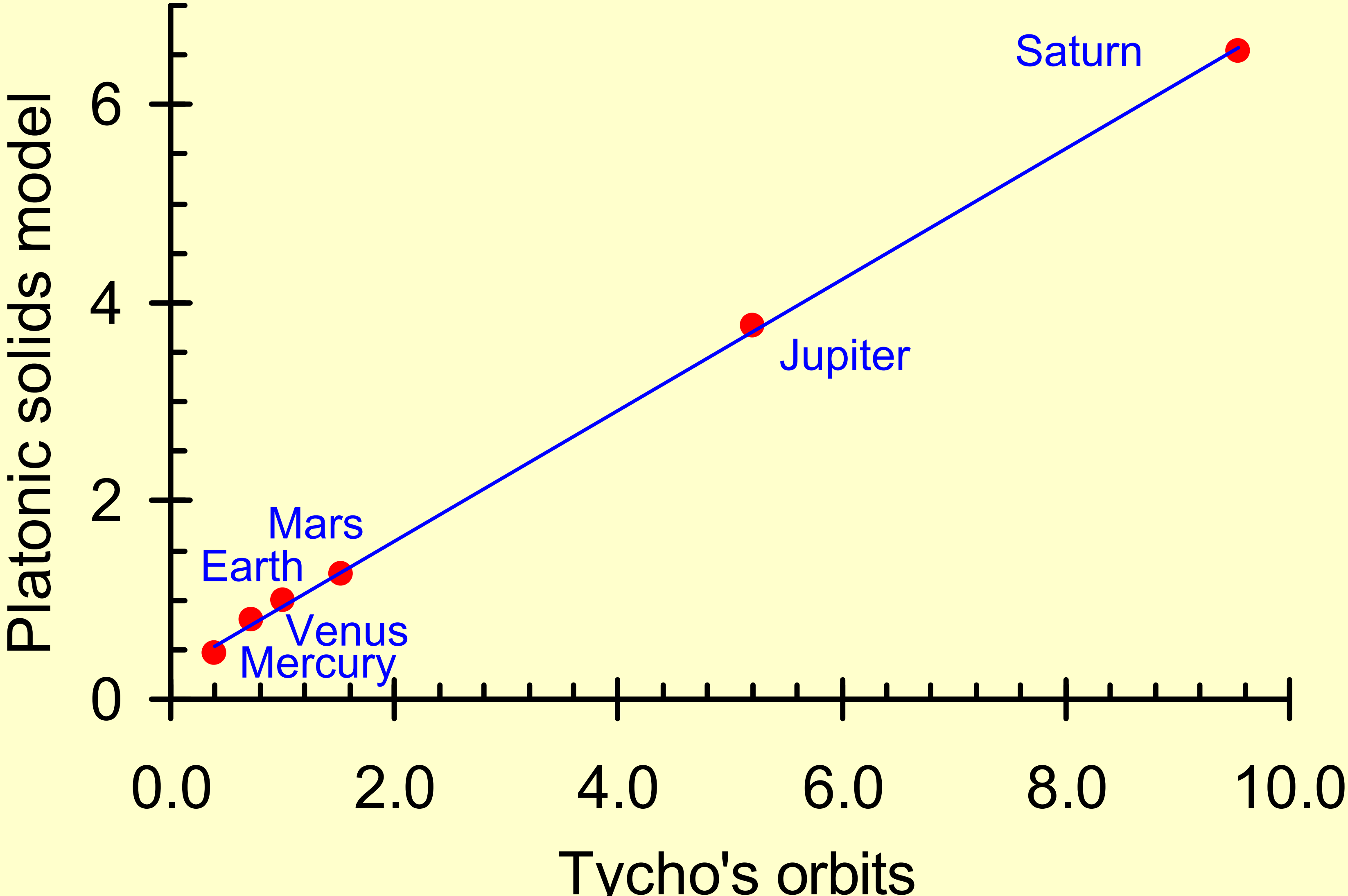




Can we explain the distances of the six planets from the sun by nesting them inside the five regular solids plus a sphere?

Keppler's *Mysterium Cosmographicum* (1596)

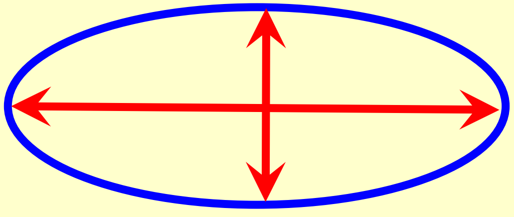
The Mystery of the Cosmos: Forerunner of the Cosmological Essays, Which Contains the Secret of the Universe; on the Marvellous Proportion of the Celestial Spheres, and on the True and Particular Causes of the Number, Magnitude, and Periodic Motions of the Heavens; Established by Means of the Five Regular Geometric Solids

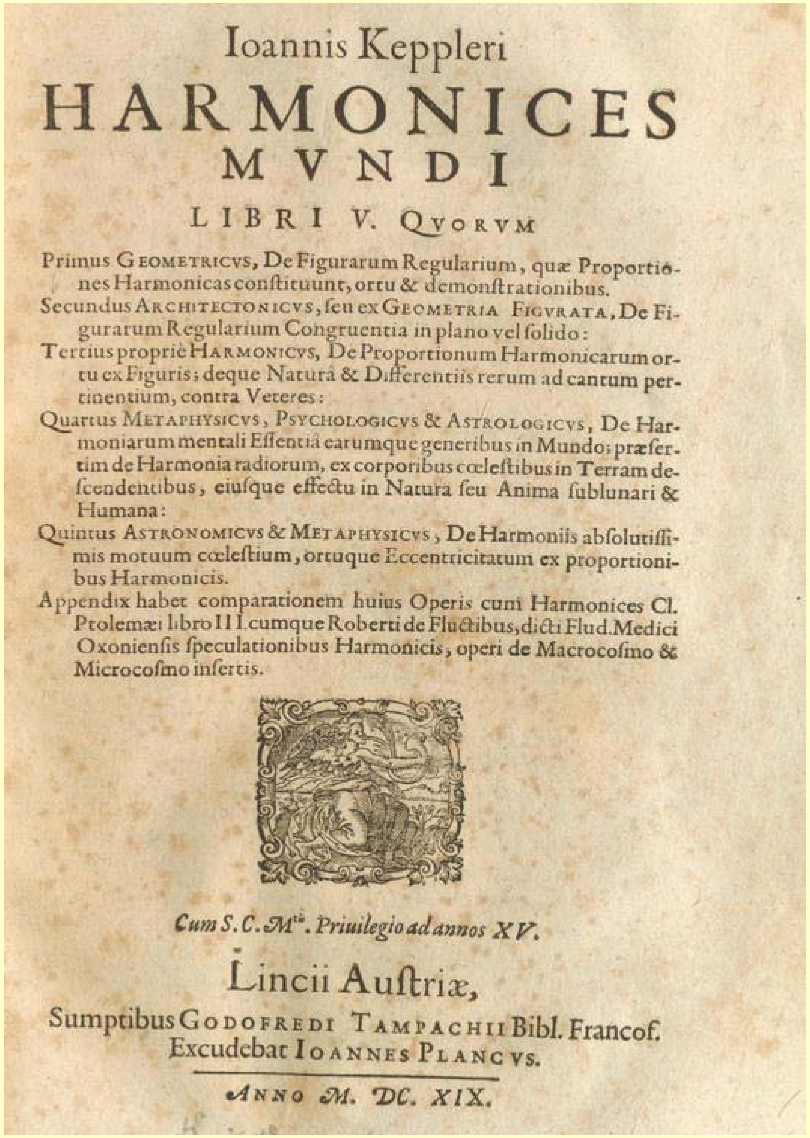


Distances from the sun in earth units

1619

But the orbit of mercury is an ellipse: the ratio of the major to the minor axis is 1.23!





Ioannis Keppleri

HARMONICES MVNDI

LIBRI V. QVORVM

Primus GEOMETRICVS, De Figurarum Regularium, quæ Proportiones Harmonicas constituunt, ortu & demonstrationibus.

Secundus ARCHITECTONICVS, seu ex GEOMETRIA FIGVRATA, De Figurarum Regularium Congruentia in plano vel solido:

Tertius propriè HARMONICVS, De Proportionum Harmonicarum ortu ex Figuris; deque Naturâ & Differentiis rerum ad cantum pertinentium, contra Veteres:

Quartus METAPHYSICVS, PSYCHOLOGICVS & ASTROLOGICVS, De Harmoniarum mentali Essentiâ earumque generibus in Mundo; præsertim de Harmonia radiorum, ex corporibus cœlestibus in Terram descendentibus, eiusque effectu in Natura seu Anima sublunari & Humana:

Quintus ASTRONOMICVS & METAPHYSICVS, De Harmoniis absolutissimis motuum cœlestium, ortuque Eccentricitatum ex proportionibus Harmonicis.

Appendix habet comparationem huius Operis cum Harmonices Cl. Ptolemæi libro III. cumque Roberti de Fluctibus, dicti Flud. Medici Oxoniensis speculationibus Harmonicis, operi de Macrocosmo & Microcosmo insertis.

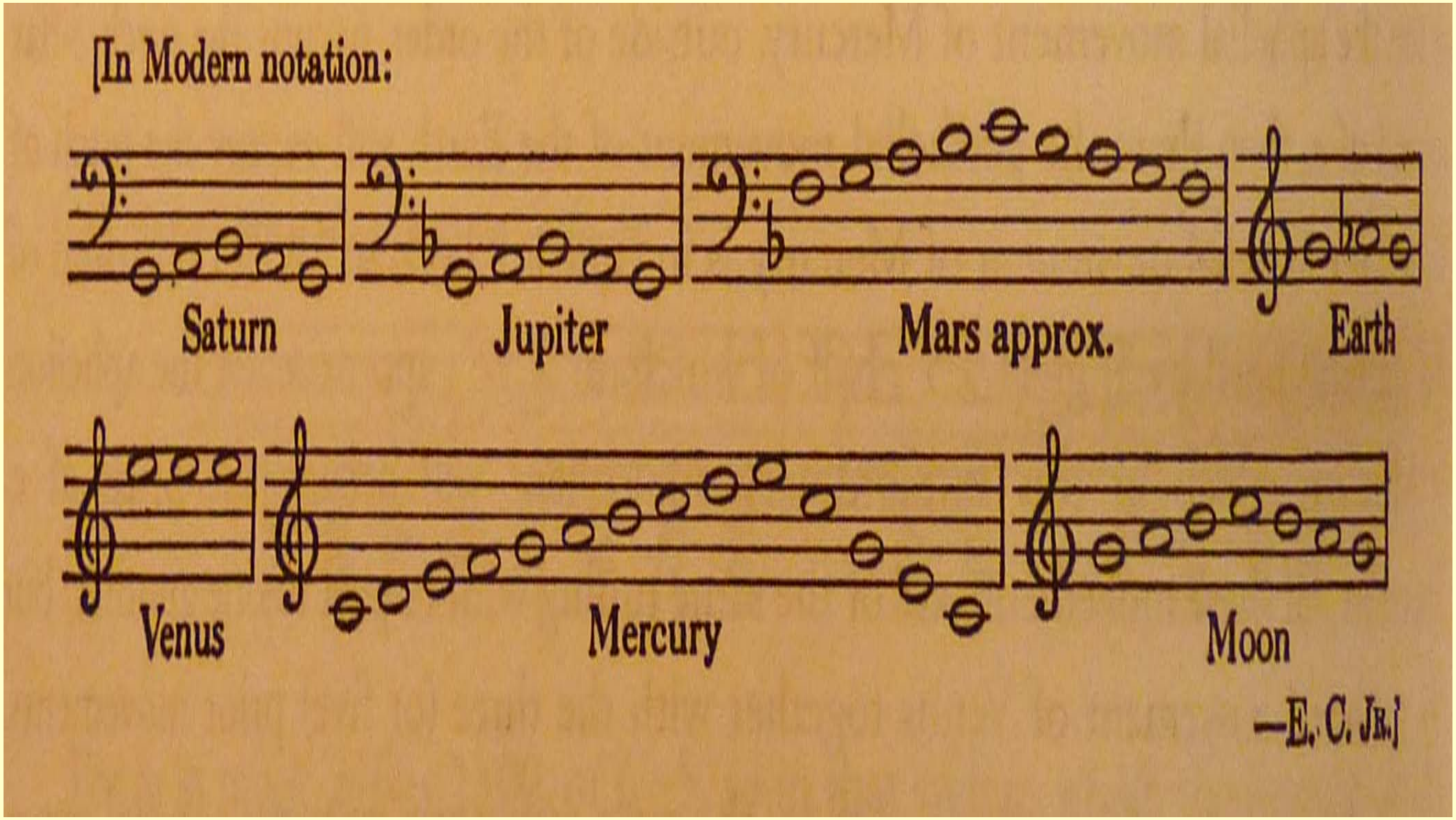
Cum S. C. Mtis. Priuilegio ad annos XV.

Lincii Austriæ,

Sumptibus GODOFREDI TAMPACHII Bibl. Francof.

Excudebat IOANNES PLANCVS.

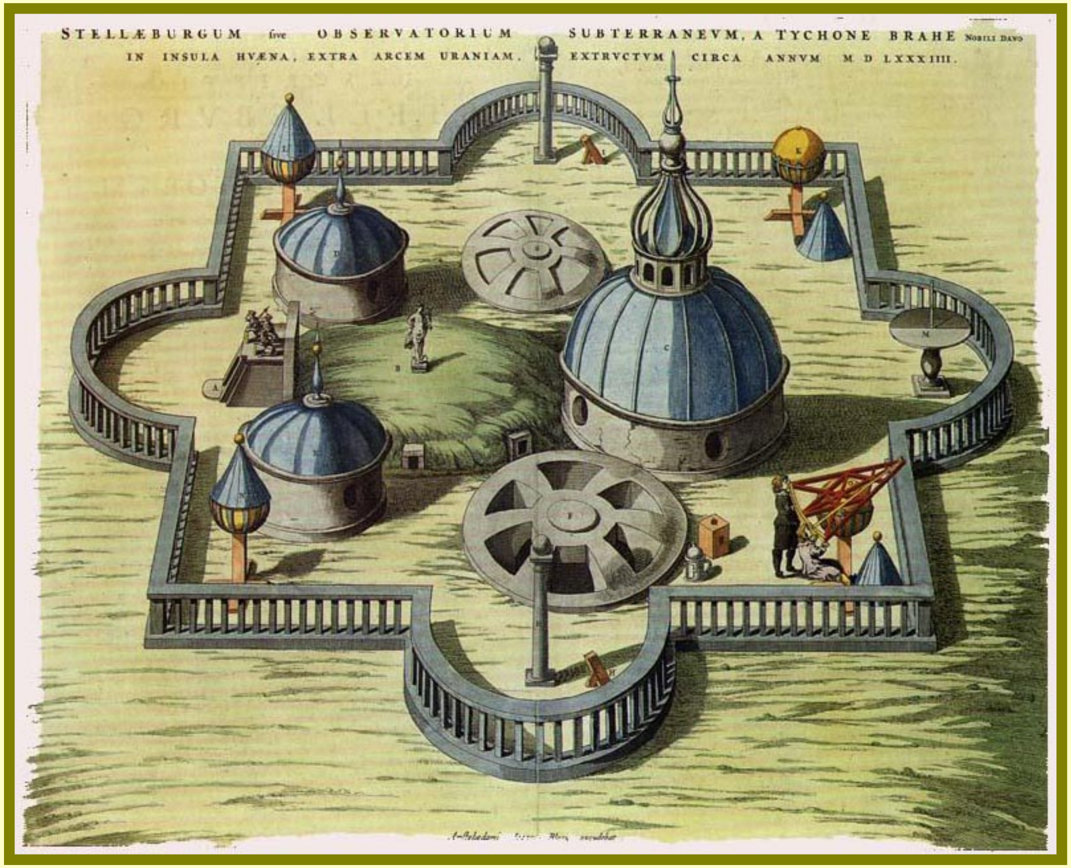
ANNO M. DC. XIX.



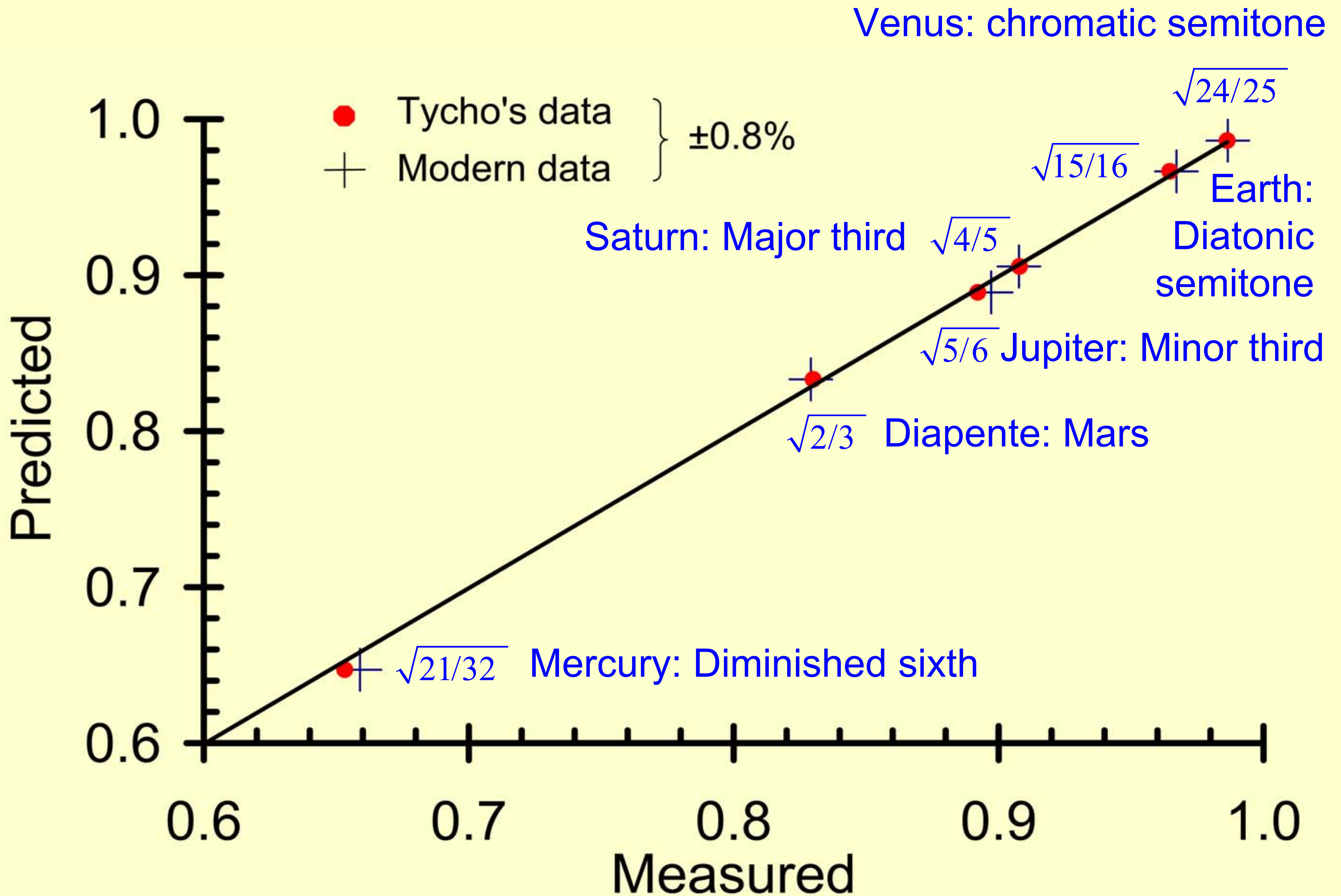
So Kepler tries to explain the eccentricity of the orbits using musical scales

http://en.wikipedia.org/wiki/Harmonices_Mundi and http://www.keplersdiscovery.com/Harmonies.html

Brahe's observatory



The five regular solids and the various musical scales turned out to be completely irrelevant. But Kepler was a meticulous scientists and relied on the very accurate data that Brahe had collected. So we will cheat and get our data from Google



Perihelion/Aphelion

Lesson 5

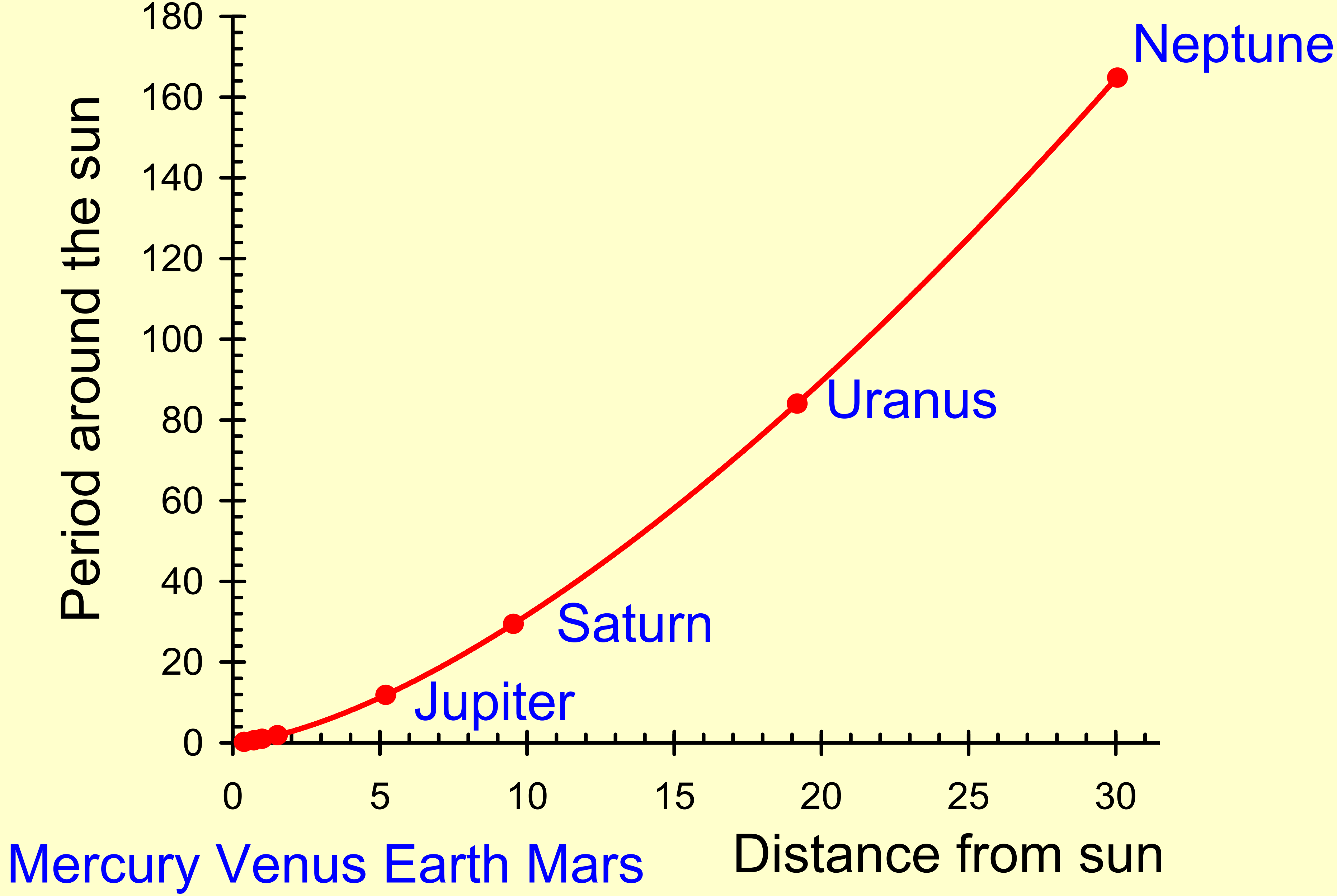
Listen to the data!

All knowledge of reality starts from experience and ends in it. Because Galileo saw this, and drummed it into the scientific world, he is the father of modern science altogether.

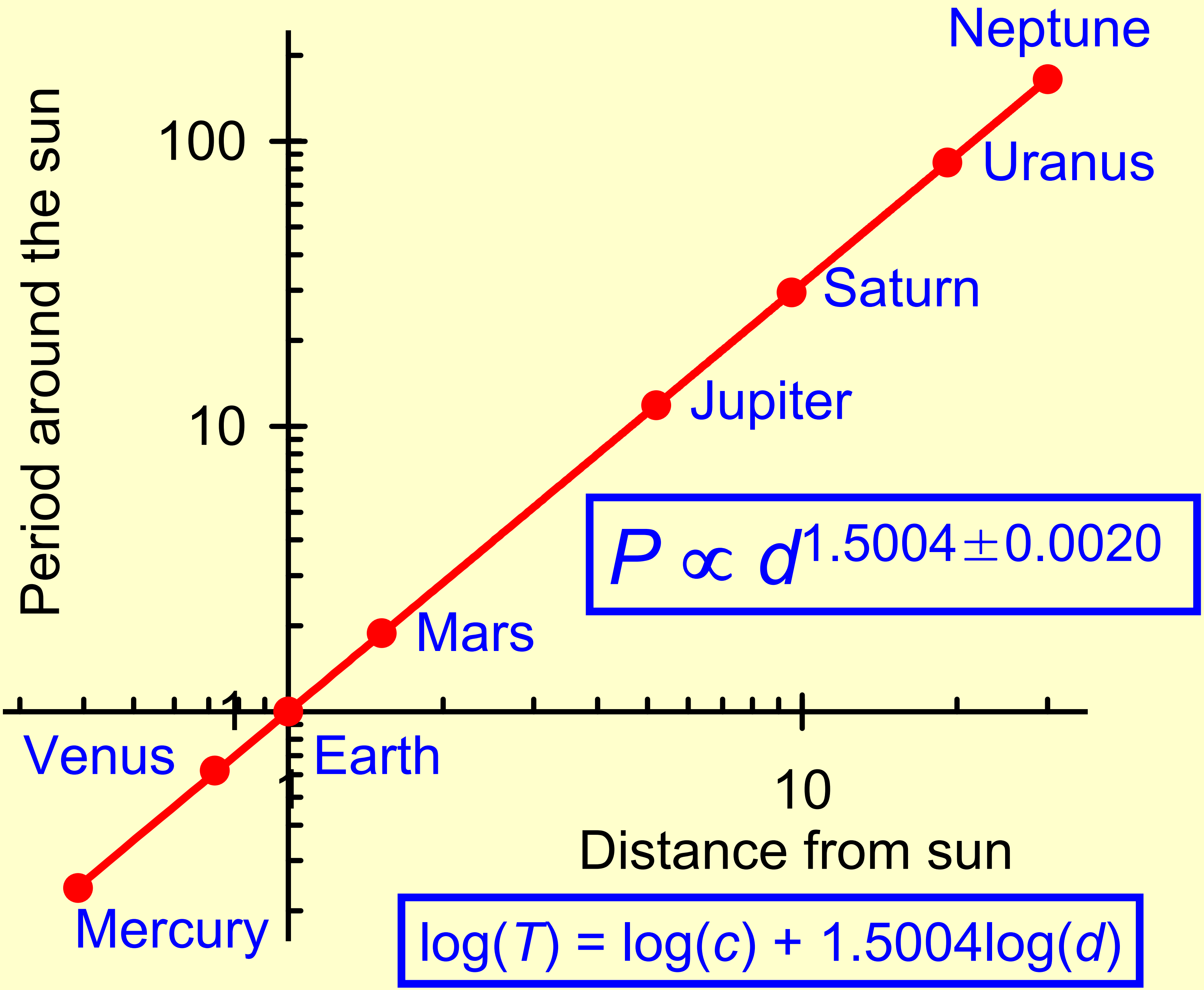
A. Einstein 'On the method of theoretical physics' The Herbert Spencer Lecture, Oxford, June 10, 1933.

	Distance	Period
Mercury	0.39	0.24
Venus	0.72	0.62
Earth	**1.00**	**1.00**
Mars	1.52	1.88
Jupiter	5.20	11.86
Saturn	9.54	29.46
Uranus	19.18	84.01
Neptune	30.06	164.80

The distance of the planets from the sun and the time it takes them to go round the sun (in earth units; also called astronomical units or A.U.)



Period around the sun
180
160
140
120
100
80
60
40
20
0
0
5
10
15
20
25
30
Distance from sun
Neptune
Uranus
Saturn
Jupiter
Mercury Venus Earth Mars



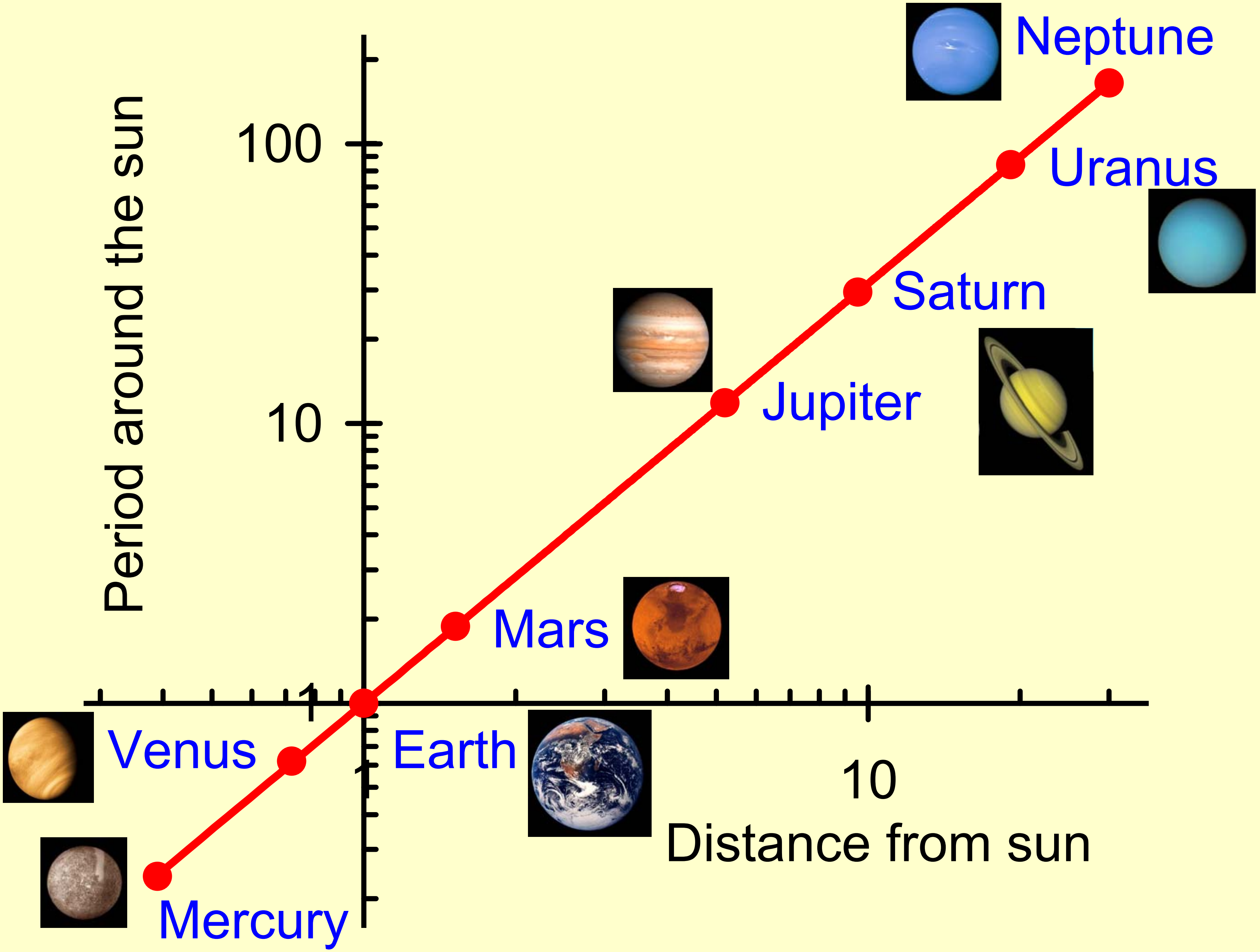
Period around the sun
100
10
1
Distance from sun
1
10
Mercury
Venus
Earth
Mars
Jupiter
Saturn
Uranus
Neptune
$P \propto d^{1.5004 \pm 0.0020}$
$\log(T) = \log(c) + 1.5004\log(d)$

Lesson 6

Don't expect it to be easy!

[the right ratio of the periodic times to the orbits] was conceived mentally on the 8th March in this year 1618 but submitted to calculation and rejected as false; summoned back on the 15th May, [and] with a fresh assault outfought the darkness of my mind afforded by my labour of 17 years on Brahe's observations. . But it is absolutely certain and exact that the periodic times of [the] planets is [proportional] to their mean distance from the sun [to the power of] 3/2.

Kepler J. *Harmonice mundi* (1619) in Sambursky S, *Physical Thought from the Presocratics to the Quantum Physicists* (London, 1974) p. 213.


Neptune
Uranus
Saturn
Jupiter
Mars
Earth
Venus
Mercury
100
10
1
1
10
Period around the sun
Distance from sun

But now we have a new question!

If the sun exerts an attractive force on each planet what is the nature of this force? Why does it depend on the distance but not the colour, shape, size or even the mass of the planet?

Lesson 7

Every answer raises new questions

Philosophy is to be studied, not for the sake of [the] answers but rather for the sake of the questions because [the] questions enlarge our conception of what is possible, enrich our imagination and diminish the dogmatic assurance which closes the mind against speculation.

Russell, B. *The Problems of Philosophy* (London, 1936) p. 250

Keppler, J. (1571-1630)

Gravity declines as $$G \propto \frac{1}{r}$$

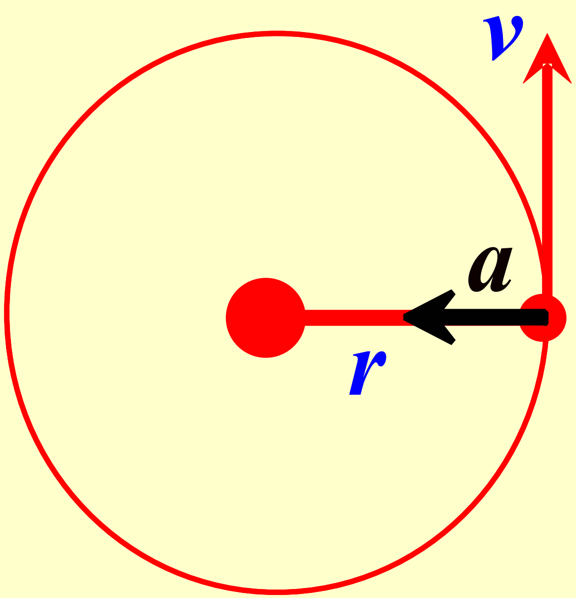
Bullialdus, I. (1605-1694)

[The] power by which the Sun holds the planets becomes weaker as in the case of light with the square of the distance [from the Sun].

$$G \propto \frac{1}{r^2}$$

Newton, I. (1642-1727)

What if gravity follows an inverse square law?



$$F = m_p a = \frac{m_p v^2}{r} = G\frac{m_s m_p}{r^2}$$

$$v \propto \frac{1}{\sqrt{r}} \qquad P = \frac{2\pi r}{v} \propto r^{3/2}$$

$$P \propto r^{1.5}$$

If gravity goes as 1/*r* then $P \propto r$

Lesson 8

Do the mathematics!

Modern [as opposed to mediaeval or ancient] science is the mathematization of hypotheses about nature combined with rigorous experimentation.

Interviewed in ‘Joseph Needham’ Channel 4 television, 6:00 pm on 13.8.88.

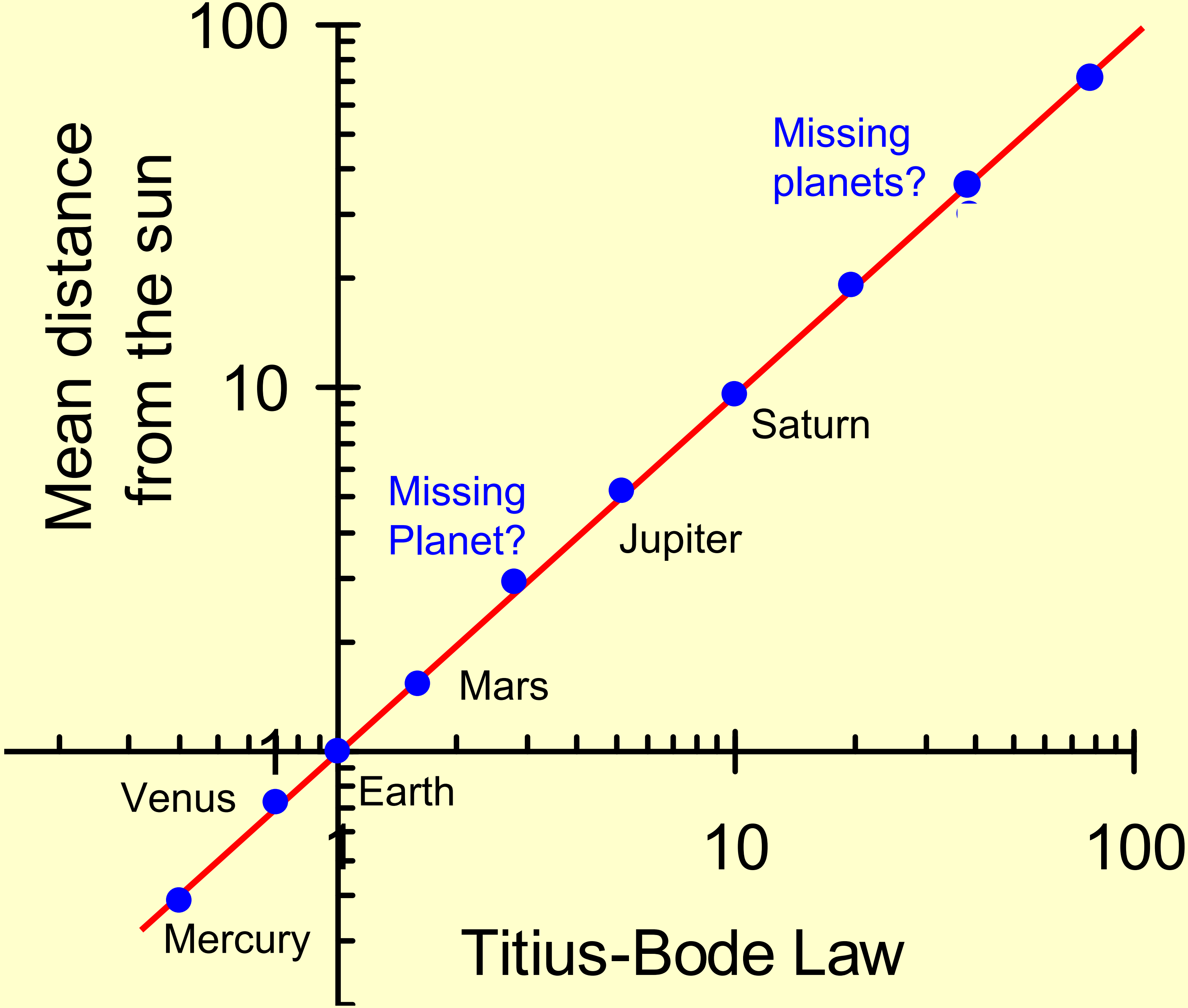
Titius-Bode Law

Discovered in 1766 by Johann Titius; published (without attribution) in 1772 by Johann Bode. The distance of each planet from the sun is given by

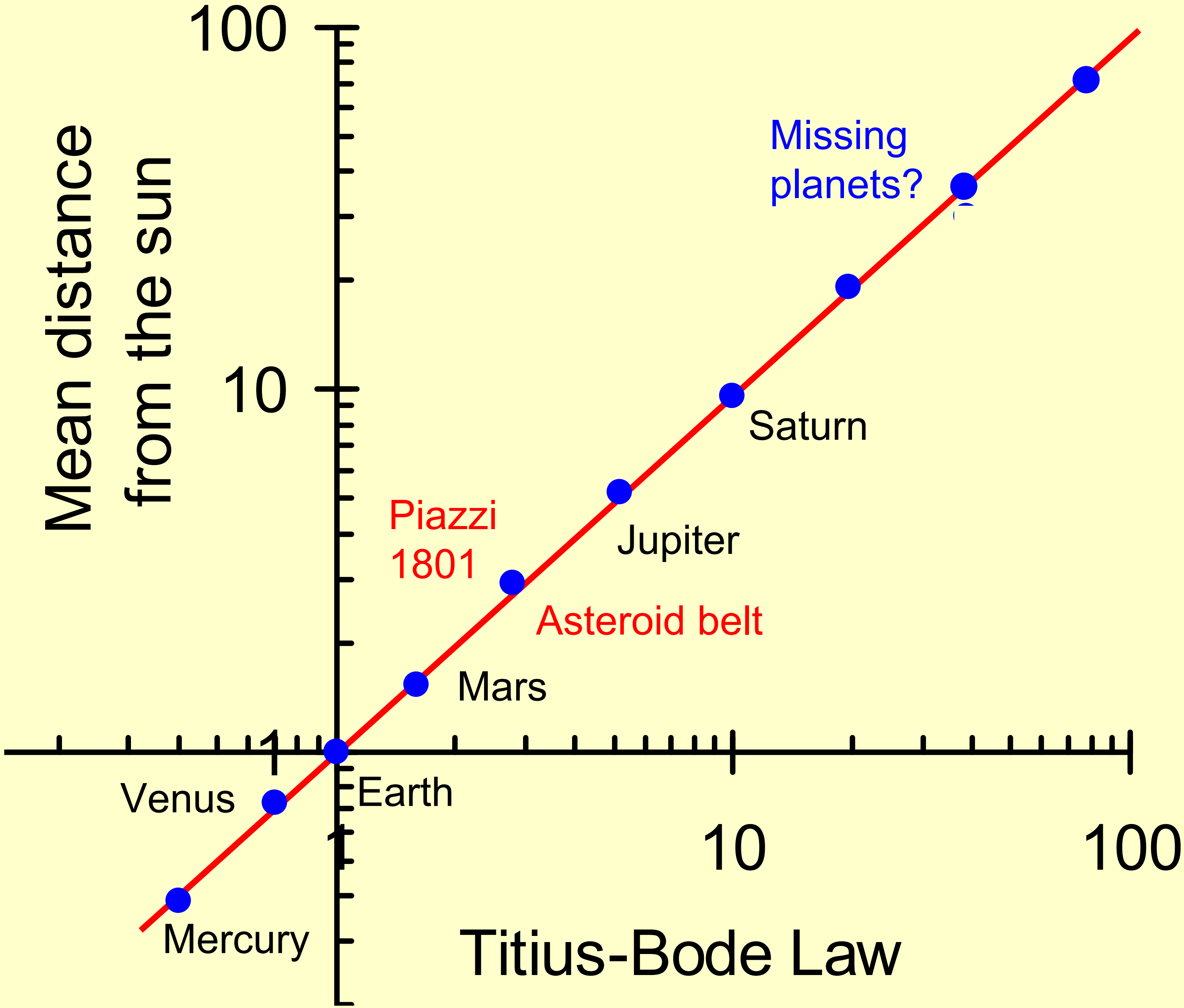
$$d = \frac{4+3\times 2^n}{10}$$

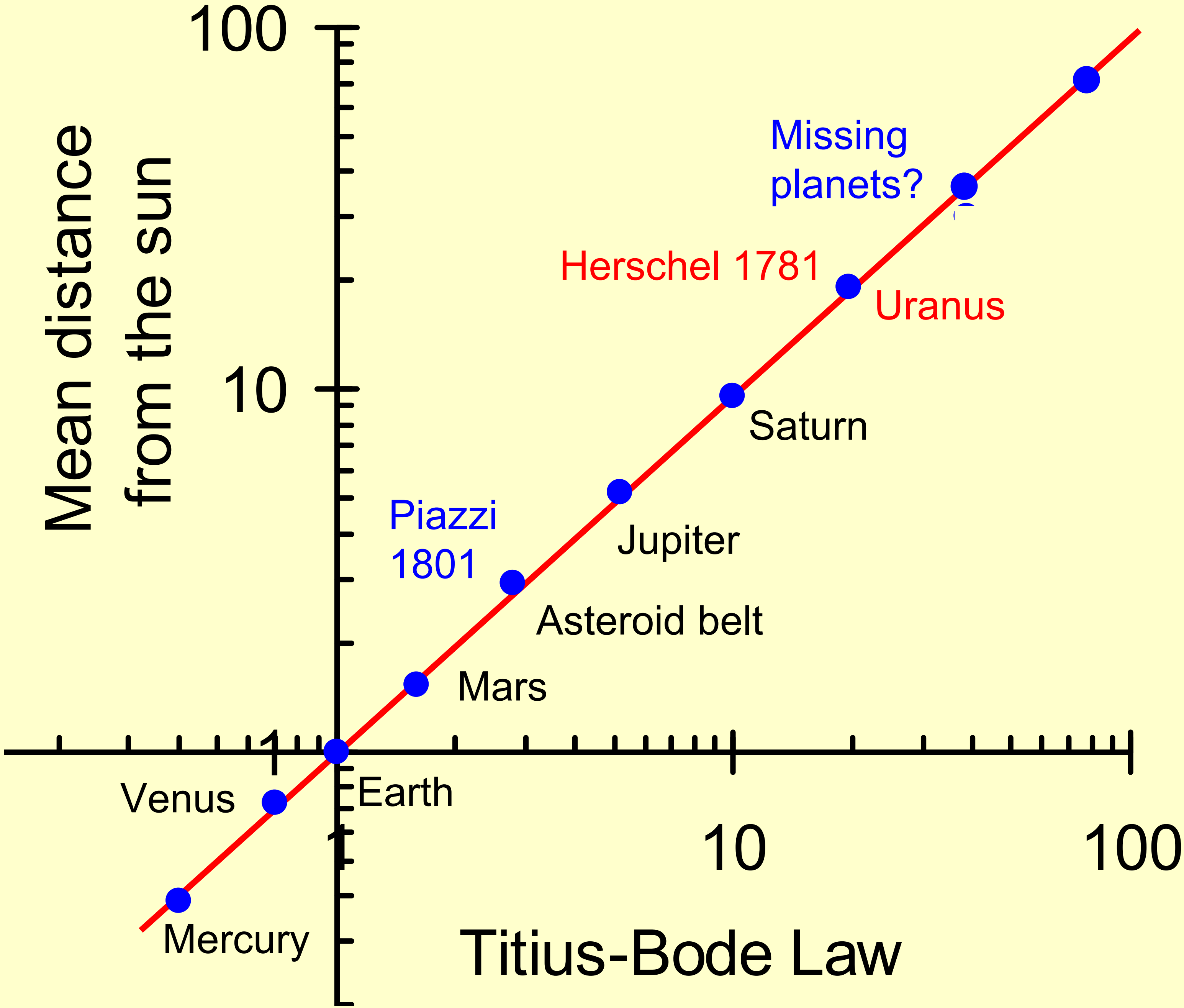
Mercury = $-\infty$; Venus = 0; Earth = 1 .

http://milan.milanovic.org/math/english/titius/titius.html

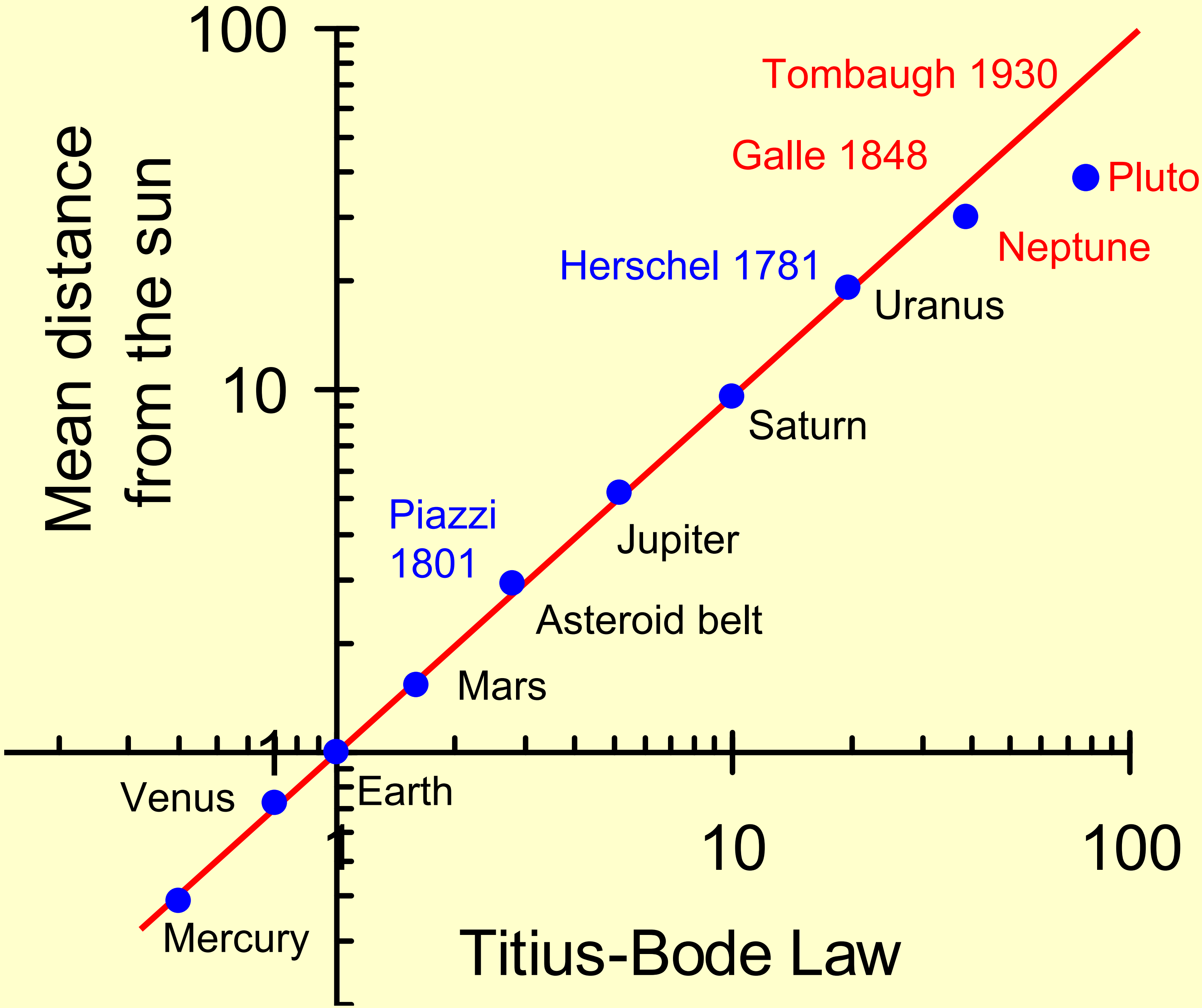


Mean distance
from the sun
100
10
1
Missing
planets?
Saturn
Missing
Planet?
Jupiter
Mars
Venus
Earth
Mercury
1
10
100
Titius-Bode Law


Mean distance from the sun
100
10
1
Missing planets?
Saturn
Jupiter
Piazzi 1801
Asteroid belt
Mars
Earth
Venus
Mercury
1
10
100
Titius-Bode Law



Mean distance
from the sun
100
10
1
Missing
planets?
Herschel 1781
Uranus
Saturn
Piazzi
1801
Jupiter
Asteroid belt
Mars
Venus
Earth
Mercury
1
10
100
Titius-Bode Law



Mean distance from the sun
100
10
1
1
10
100
Tombaugh 1930
Galle 1848
Pluto
Neptune
Herschel 1781
Uranus
Saturn
Piazzi 1801
Jupiter
Asteroid belt
Mars
Earth
Venus
Mercury
Titius-Bode Law

Lesson 9

Beware of false associations!

Or

Predictions are a necessary but not sufficient condition for being right!

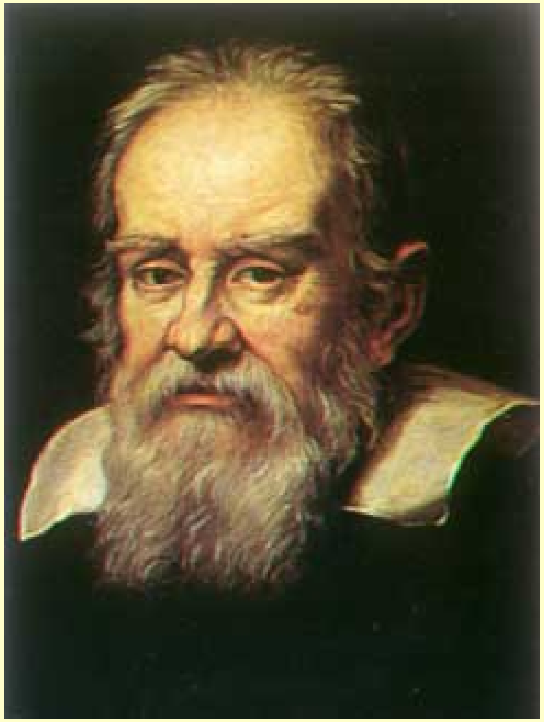
Feynman, R.

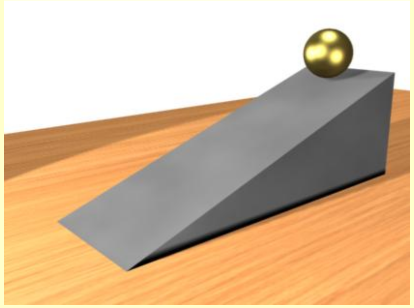
Yes, you told us what happens, but what is gravity? Where does it come from? Do you mean to tell me that a planet looks at the sun, sees how far it is, calculates the inverse square of the distance and then decides to move in accordance with that law?

The Character of a Physical Law (MIT Press, Cambridge, Massachusetts, 1980) p. 33.

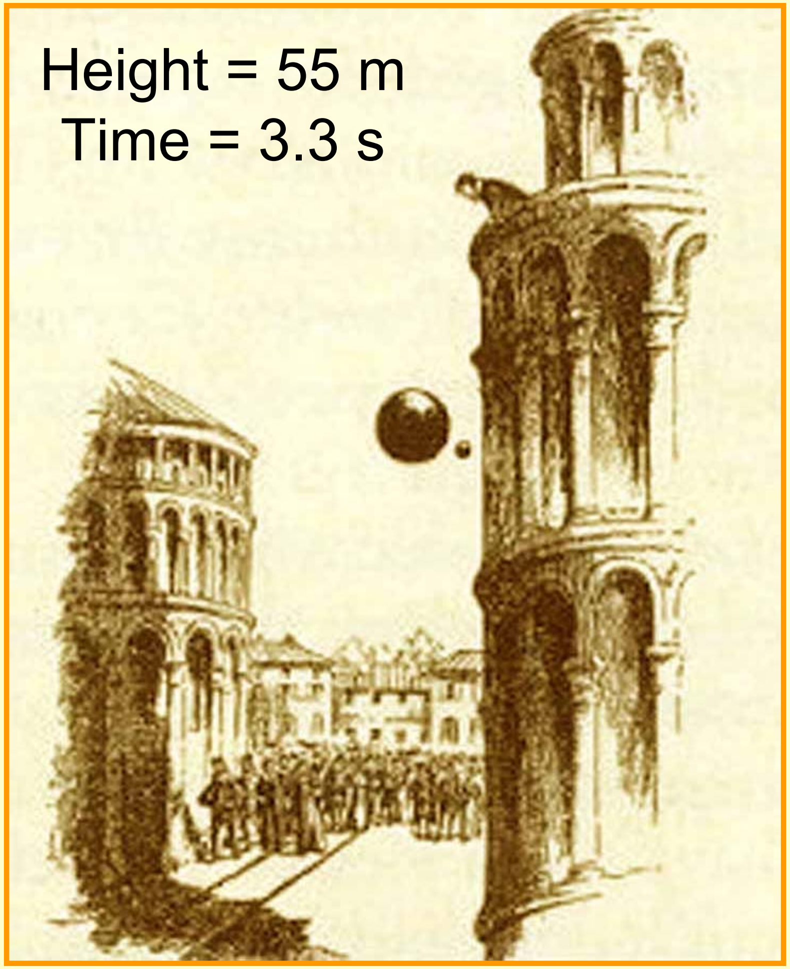
Galileo Galilei 1564–1642

The first great experimentalist

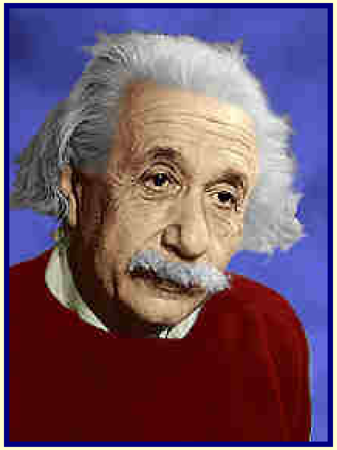




$$x = \frac{1}{2} a t^2$$



So: why do heavy and light objects fall at the same speed?



Einstein/Galileo

$$G\frac{m_s m_p}{r^2} = \frac{m_p v^2}{r}$$

The mass of the planet on the left is the gravitational mass; the mass of the planet on the right is the inertial mass. But they cancel EXACTLY.

Perhaps they are really the same thing!
If the gravity of the sun curves space and time, each planet is just following the natural curve of space-time and its mass no longer matters.

Before Einstein

How can we explain the fact that heavy and light objects fall (in a vacuum) at exactly the same speed.

After Einstein

What if we start from the equivalence of gravitational mass and inertial mass; what else would we have to change?

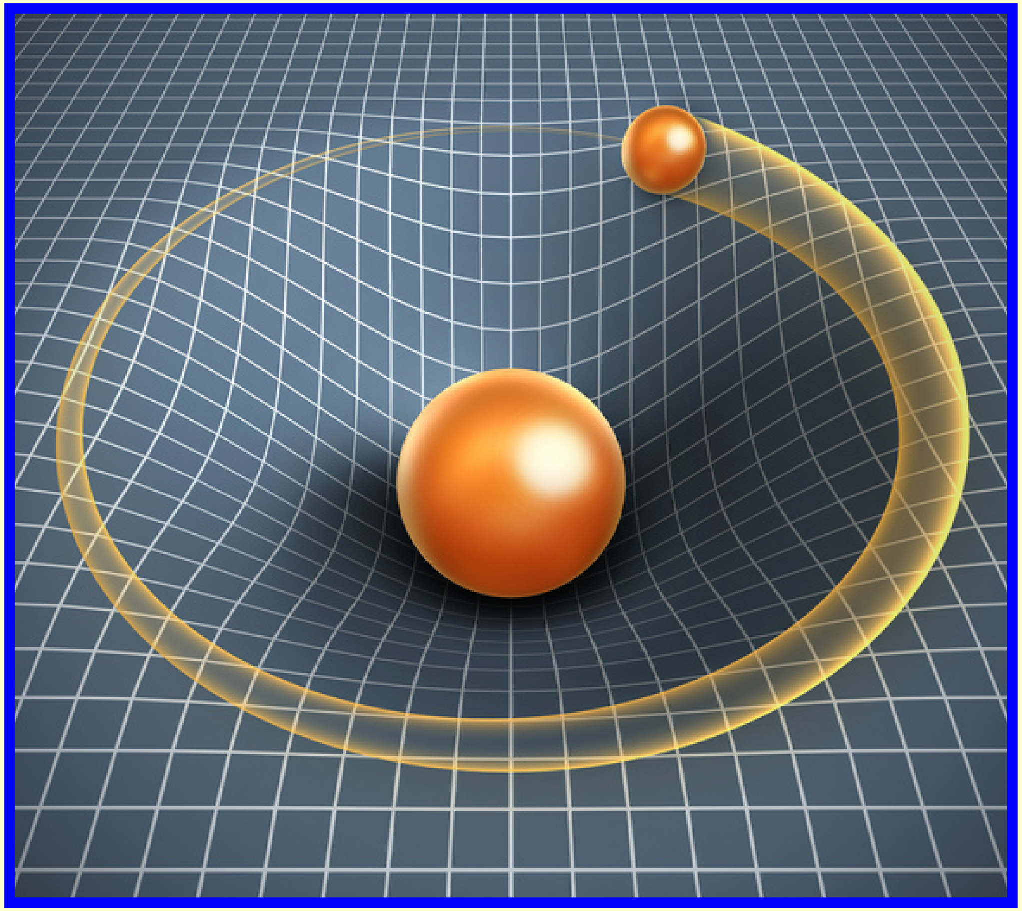
We have to bend space and time!

Einstein in his own words

I was sitting in a chair in the patent office at Bern when all of a sudden a thought occurred to me: 'If a person falls freely he will not feel his own weight'. I was startled. This simple thought made a deep impression on me. It impelled me toward a theory of gravitation.

Kyoto Lecture reported by J. Ishiwara in Einstein Koen-Roku, (Tokyo-Tosho, Tokyo, 1977)

What if heavy objects curve space and time?



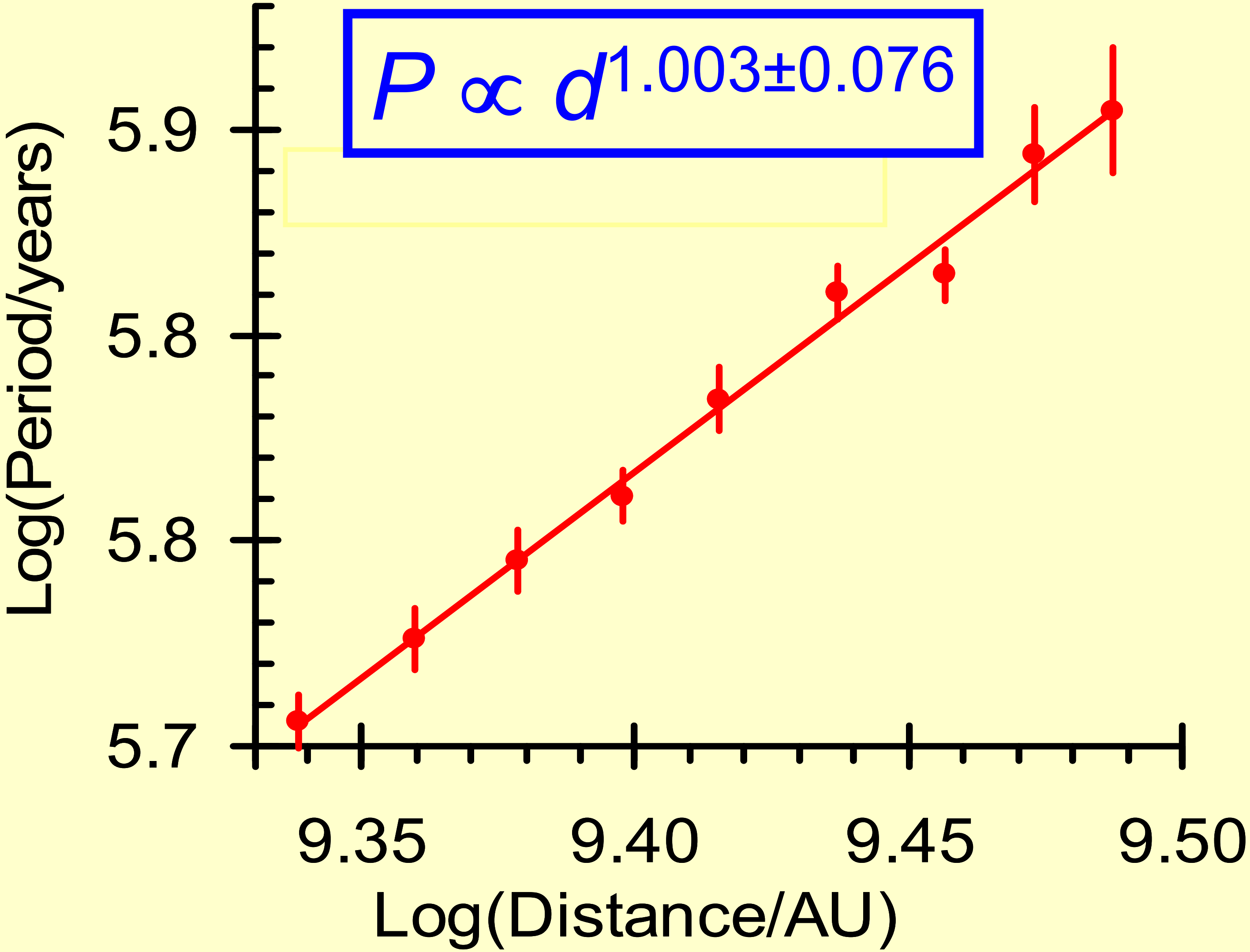
Then the earth doesn't have to know where the sun is: it just follows the curvature of space-time

Lesson 9

If you can’t get from the beginning to the end, try getting from the end to the beginning!

The Giraffe Galaxy: NGC 2403

Doppler measurement of rotational speed of stars



Period of rotation against distance from the centre of the Giraffe galaxy

Since the period falls as $1/r$ and not $1/r^{1.5}$ Kepler was right (for galaxies if not for solar systems) and at a galactic scale the gravitational force must decline as $1/r$ not $1/r^2$.

$$F = m_p a = \frac{m_p v^2}{r} = G\frac{m_{BH} m_p}{r}$$

$$v = Gm_{BH} \qquad P = \frac{2\pi r}{v} \propto r$$

Two possibilities:

1. The force of gravity falls as $1/r$ not $1/r^2$ when the acceleration is very weak. MOND: modified Newtonian Dynamics.
2. There is dark matter which we can't see so that $P \propto r$;

Lesson 10

The answers we have found only serve to raise a whole set of new questions. In some ways we feel that we are as confused as ever but we believe that we are confused on a higher level and about more important things.

Cambridge University Computer Centre 1970.

Lessons from the front

1. Look for interesting patterns in nature
2. When you find patterns, look for exceptions
3. When the road is blocked try a different path but always keep it simple
4. Your data are telling you the answer; learn to listen
5. It will never be easy so don’t give up
6. Every answer is the start of a new question
7. If you can’t make the data fit the theory try to make the theory fit the data
8. Whatever else you do never stop having fun!

Creativity in science is about telling stories.

- Interesting
- Persuasive
- Testable

But they are still stories!

Advice to young epidemiologists

Never make a calculation until you know the answer. Make an estimate before every calculation, try a simple biological argument (R_0, generation time, selection, survival, control). Guess the answer to every puzzle. Courage: no one else needs to know what the guess is. Therefore, make it quickly, by instinct. A right guess reinforces this instinct. A wrong guess brings the refreshment of surprise. In either case, life as an epidemiologist, however long, is more fun.

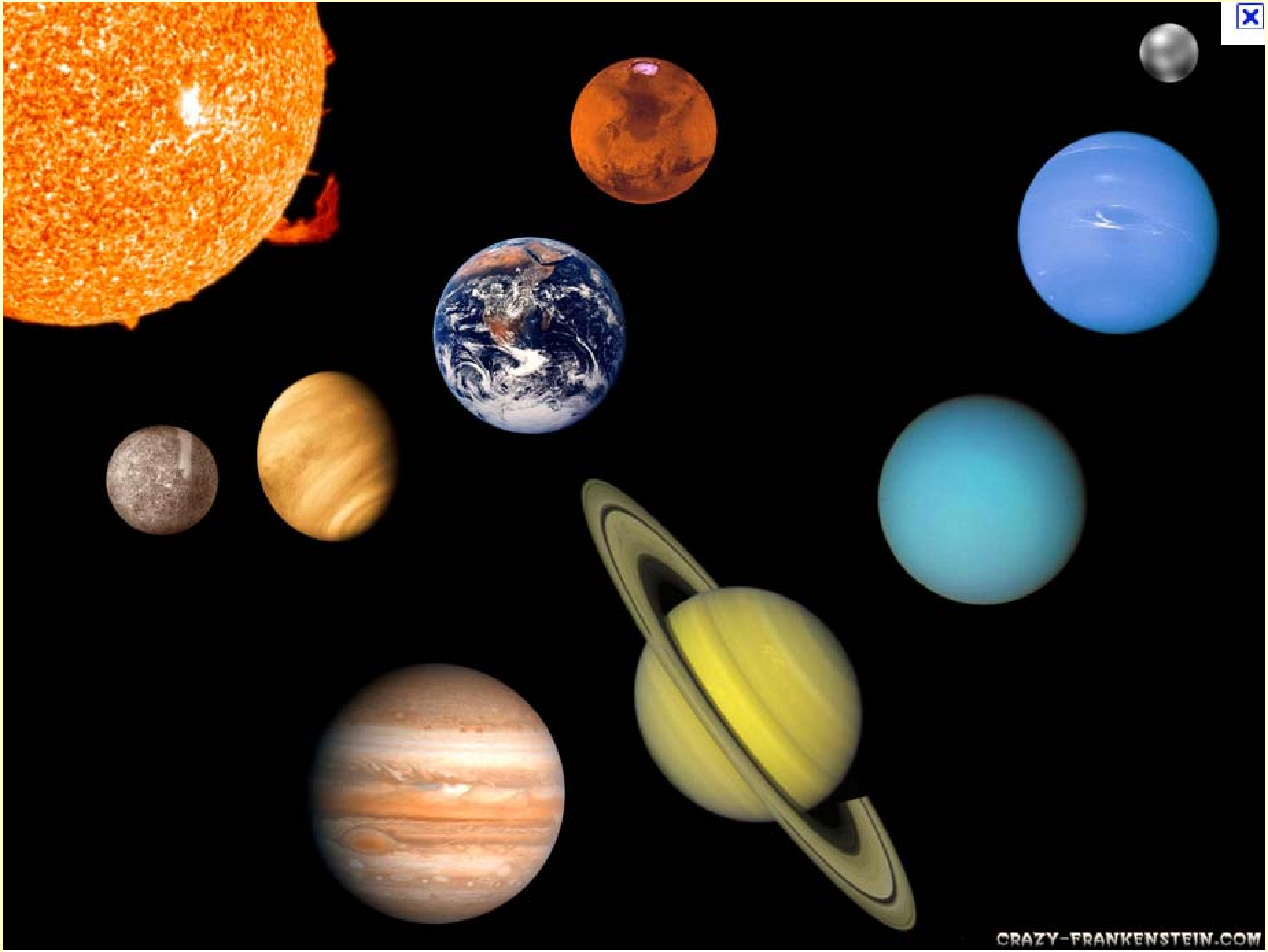
Plagiarised from E.F. Taylor and J.A. Wheeler *Space-time Physics* 1963

So what about sex?

- A women wants to pass on her genes
- Suppose there are ten girls for each boy
- Then since everyone has a mother and a father, each boy will have ten times as many children as each girl.
- To pass on her genes to lots of grand-children she is ten times better off giving birth to a boy than to a girl.
- So you are always better off producing the minority sex!

So why have sex at all?

- Our generation time is about 20 years
- The HIV virus reproduces about 1 thousand times each second
- With asexual reproduction a virus that kills you will also will your daughters
- Sexual reproduction means that your sons and your daughters have an immune system that is quite different from yours
- So we have sex to protect us from infectious diseases.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A brief history of science
(in one slide)!

Ptolemy (AD 90-168)

1. Everything goes around the earth (epicycles)

Brahe, T. (1546-1601)

2. The sun goes round the earth but the planets go round the sun.

Copernicus

3. Everything goes around the sun

Keppler, J. (1571–1630)

4. We can explain the orbits of the six planets by nesting them in the five regular Euclidean solids plus the sphere.
5. Period (of the planets) is proportional to the distance to the power of 3/2.
6. The force of the sun on the planets falls in proportion to the distance from the sun.

Bullialdus, I. (1605–1694)

7. [The] power by which the Sun holds the planets becomes weaker as in the case of light with the square of the distance [from the Sun].

Newton, I. (1642–1727)

8. If gravity follows an inverse square law Keppler's laws (and much more) follows!

Einstein, A. (1879–1955)

9. I was sitting in a chair in the patent office at Bern when a thought occurred to me: 'If a person falls freely he will not feel his own weight'. I was startled. This simple thought impelled me toward a theory of gravitation.

And now (2000 –

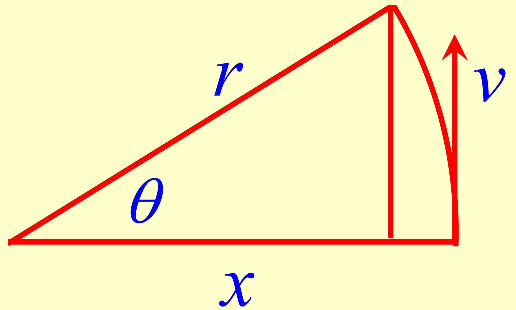
10. Period of the stars is proportional to the distance from the centre of the galaxy. At large distances Keppler was right! But is it really Dark Matter or ?

How do we play tennis?

French Open

5 June 2011

Centrifugal force



$$x = r\cos\theta = r\cos\omega t$$

Acceleration towards the centre

$$\ddot{x} = -\omega^2 x \qquad \ddot{r} = -\omega^2 r$$

Angular vs. linear velocity

$$\omega = \frac{v}{r} \qquad \ddot{r} = -\frac{v^2}{r}$$

Centrifugal force = mass × acceleration

$$F = m_p \frac{v^2}{r}$$

At a galactic scale

Either Keppler was right and the force of gravity goes down as the *distance* and not as the *distance squared* but only at very large distances. (MOND: Modified Newtonian Dynamics)

OR

Since the outer stars are going round too quickly there is *dark matter* in the universe that increases the gravitational force and increases up the rotational speed!

Under MOND we replace the Newtonian acceleration a_N by the MOND acceleration a_M :

$$a_N = a_M \mu(a_M / a_0)$$

$$\mu(a_M / a_0) = \frac{a_M / a_0}{\sqrt{1 + (a_M / a_0)^2}}$$

And we have the right limits for large and small accelerations:

$$a_M \to 0 \quad a_M \to \sqrt{a_N a_0} \propto 1 / r$$

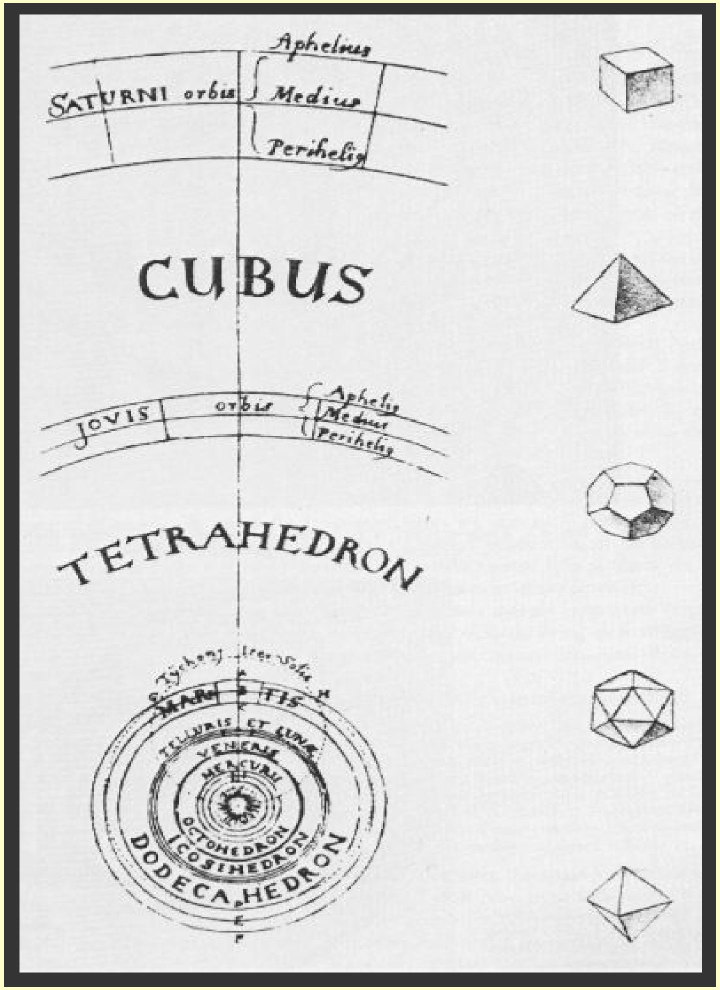
$$a_M \to \infty \quad a_M \to a_N \propto 1 / r^2$$

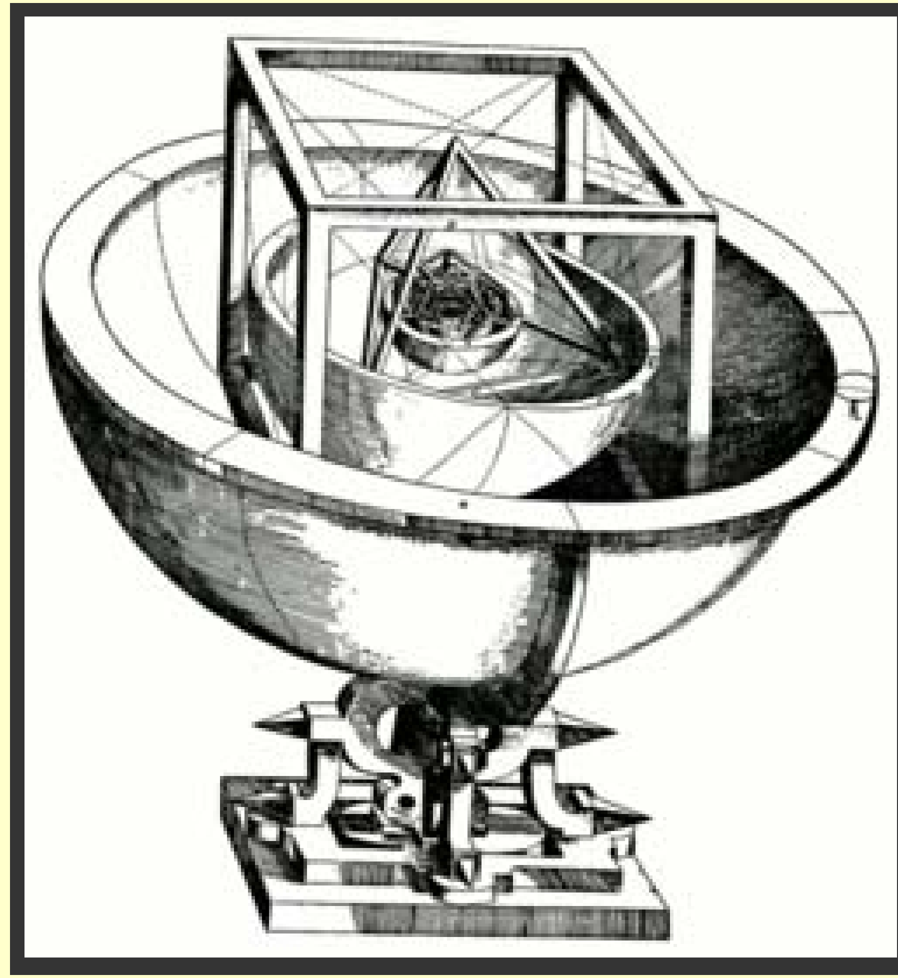
We also get a new constant of nature:

$$a_0 = 1.2 \times 10^{-10} \text{ m/s}^2$$

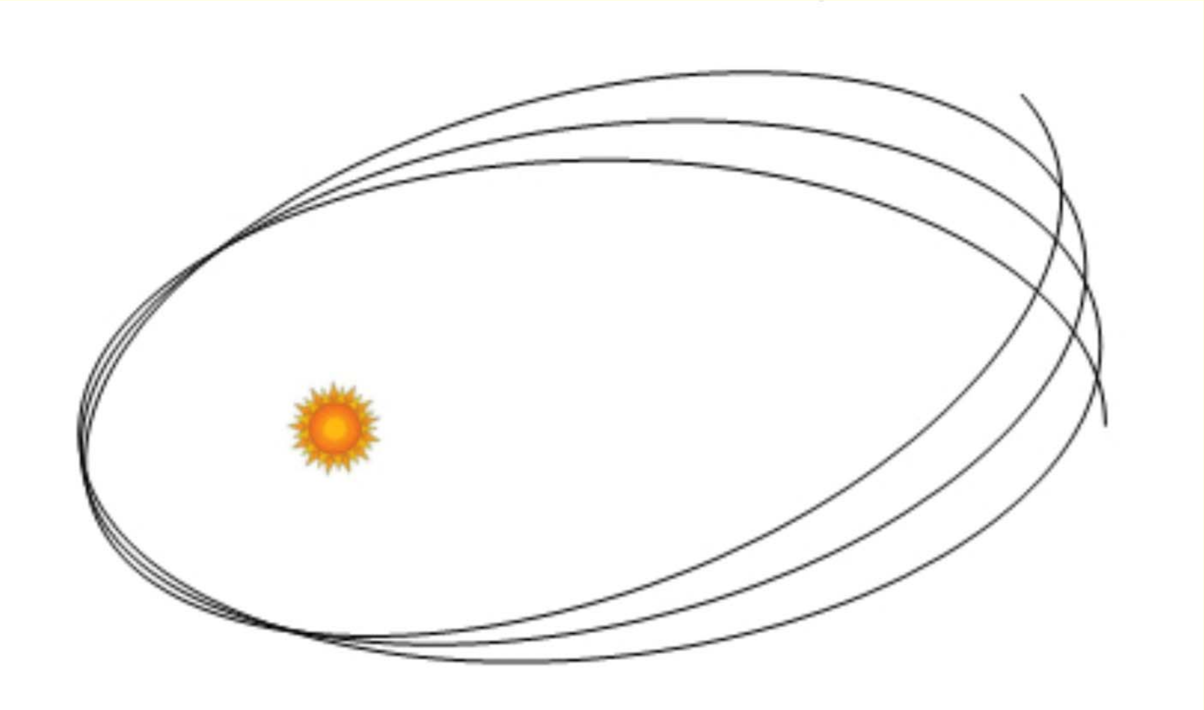
And if you want to know more see: http://arxiv.org/abs/0908.3842

Keppler's challenge





Can we explain the distances of the six planets from the sun by nesting them inside the five regular solids plus a sphere?



Using Newton's gravity equations, we can determine that the predicted advancement in the orbit should be 532 arc-seconds per century. The measured advancement however is 575 arc-seconds: 43 more than predicted. In 1915 Einstein used GR to calculate the expected amount of precession using GR and found the calculation yielded a precession of 43 arc-seconds, which precisely accounted for the difference.

http://www.alternativephysics.org/book/GRexperiments.htm