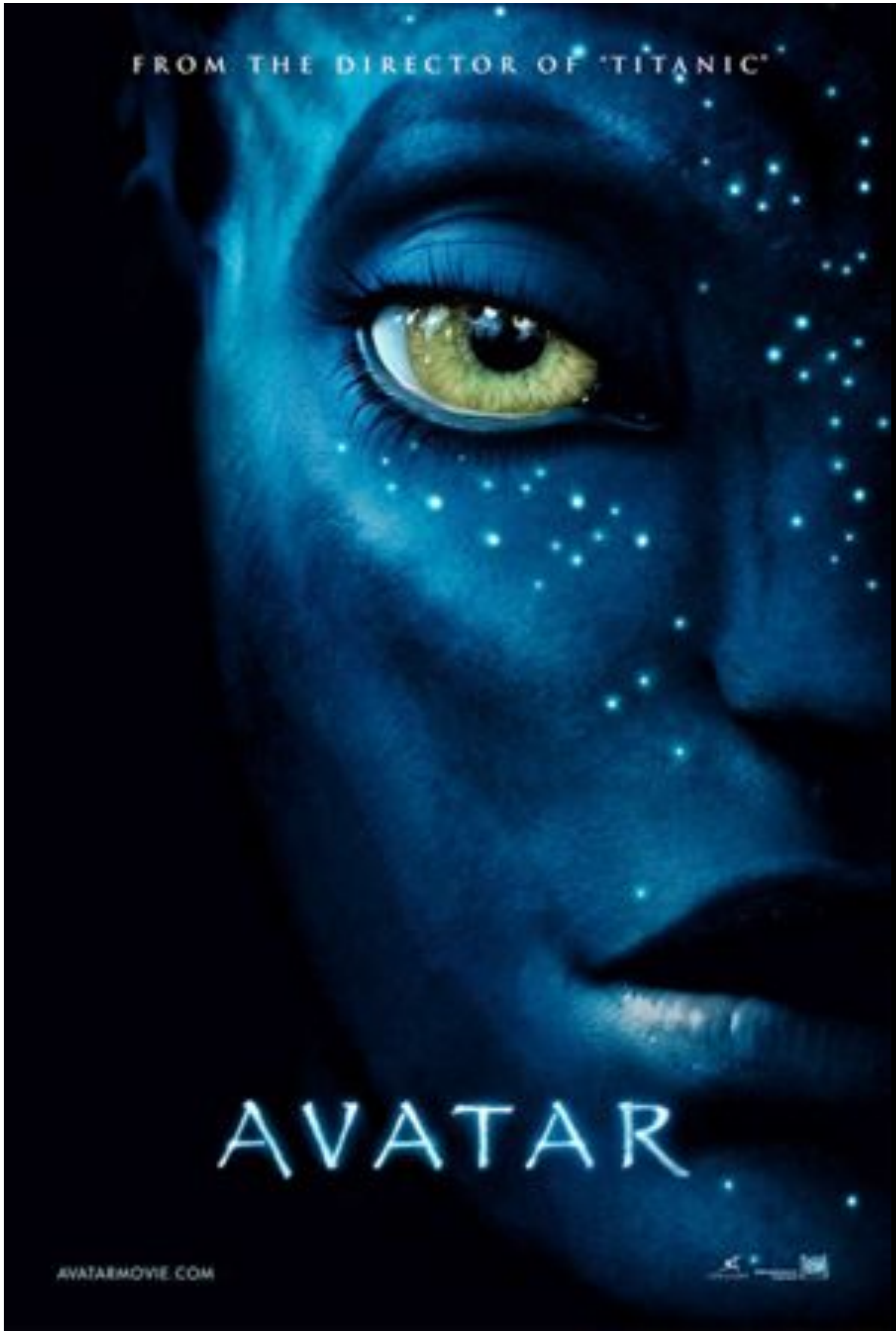
PiTP

Lectures on Quantum Phenomena

How science is really done

A tantalising tale of
duels, harems, heroines,
and… a cold case of murder

Prof. Jaymie Matthews
UBC Physics & Astronomy



Now at a theatre near you

Coming soon

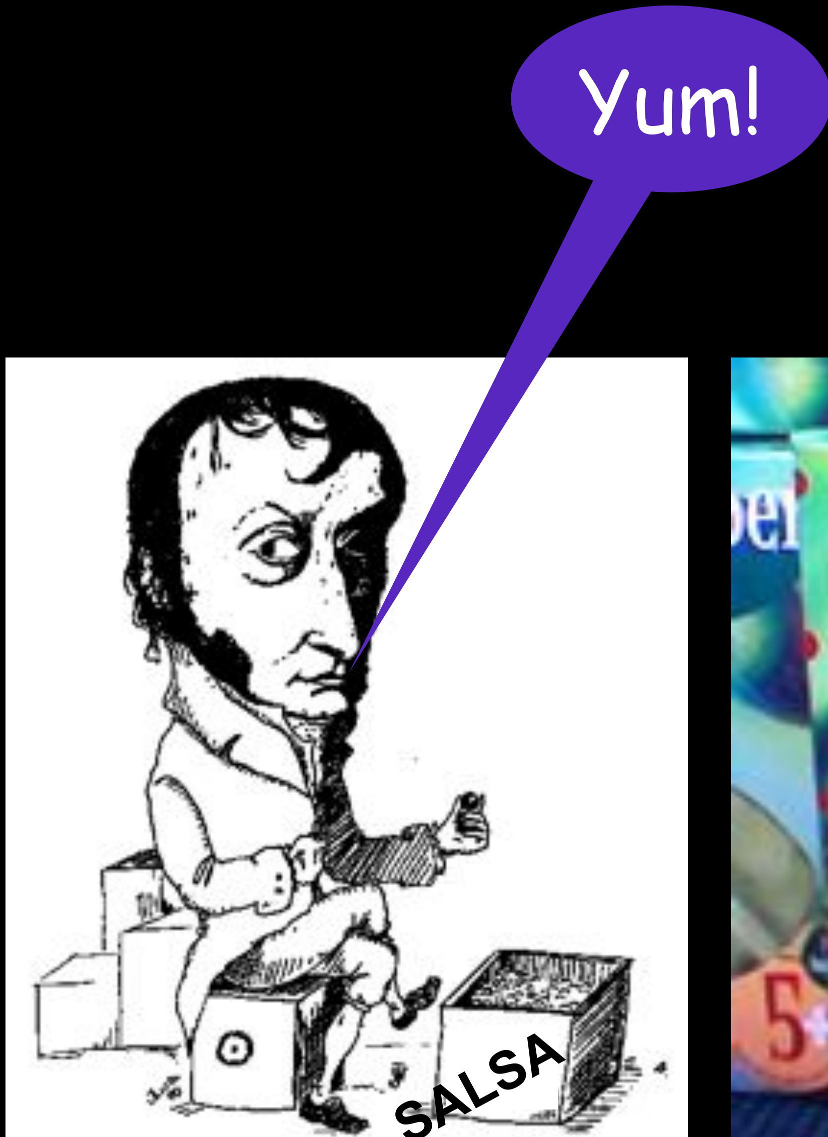
$$N_A = 6.023 \times 10^{23}$$

AVOGADRO

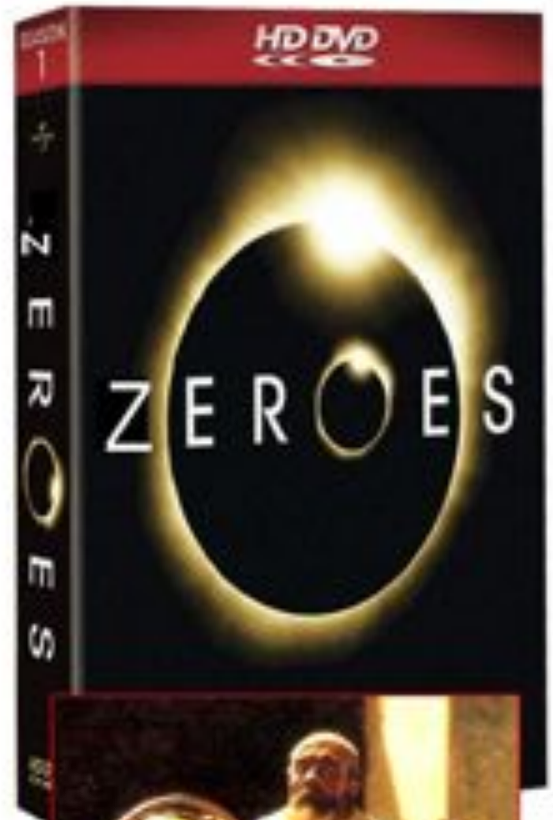
Good to the last molecule

Good to the last molecule

Great for an astro party



GaLiLeOS
gone
WILD



PAPAL
ADVISORY
EXPLICIT SCIENCE

Back to our regular programming

A Physics Trivial Pursuit question?

What's the connection between *gravity* and *life insurance*?

A Physics Trivial Pursuit question?

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A Physics Trivial Pursuit question?

What's the connection between *<u>gravity</u>* and *<u>life insurance</u>*?

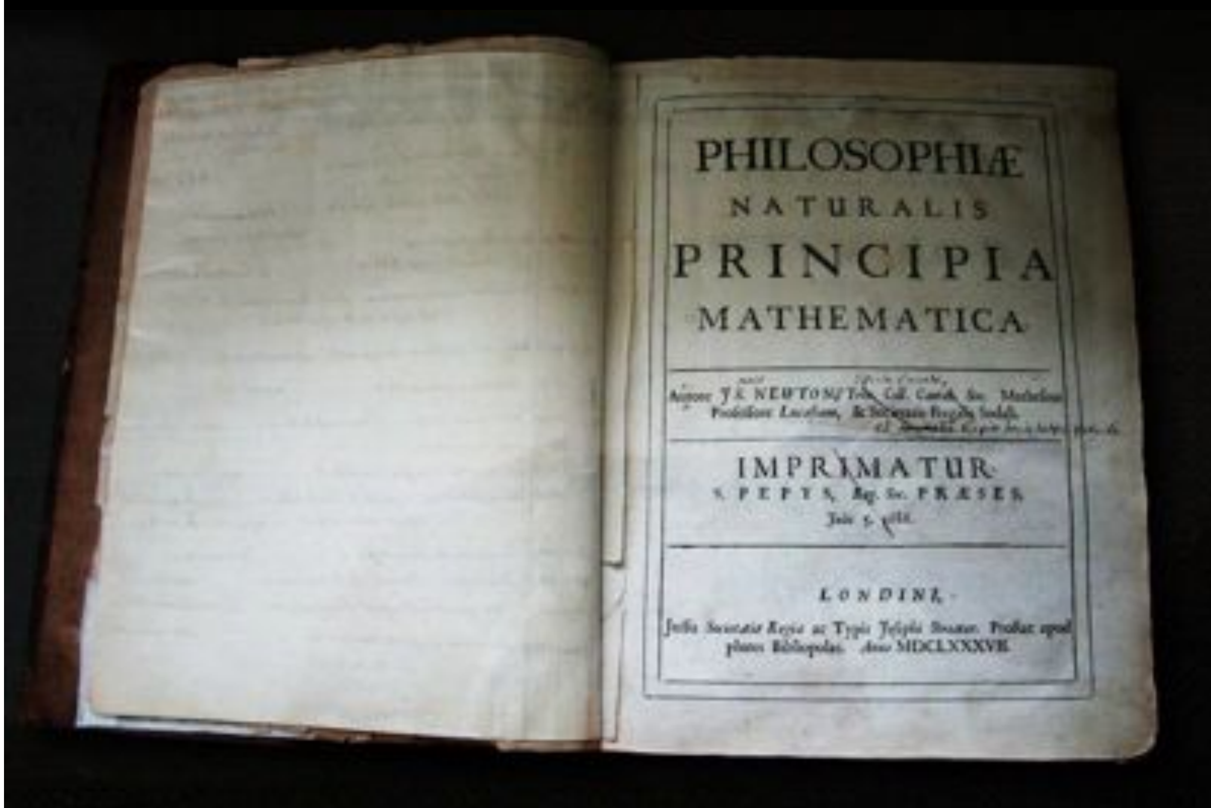
A Physics Trivial Pursuit question?

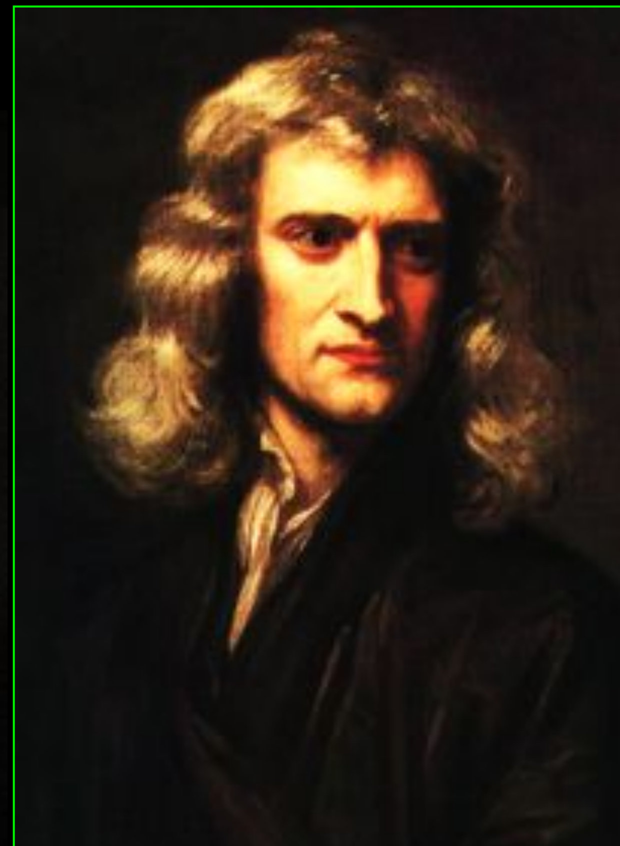
What's the connection between *gravity* and *life insurance*?

The laws of motion and gravity

My story begins with this man

Sir Isaac Newton (1643 – 1727)

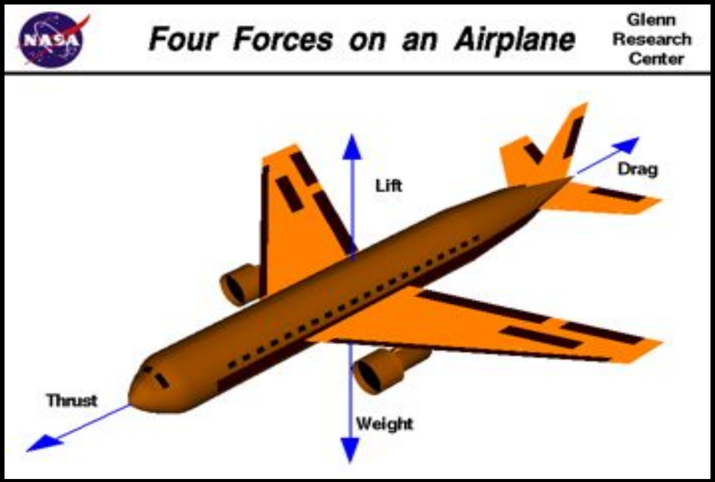


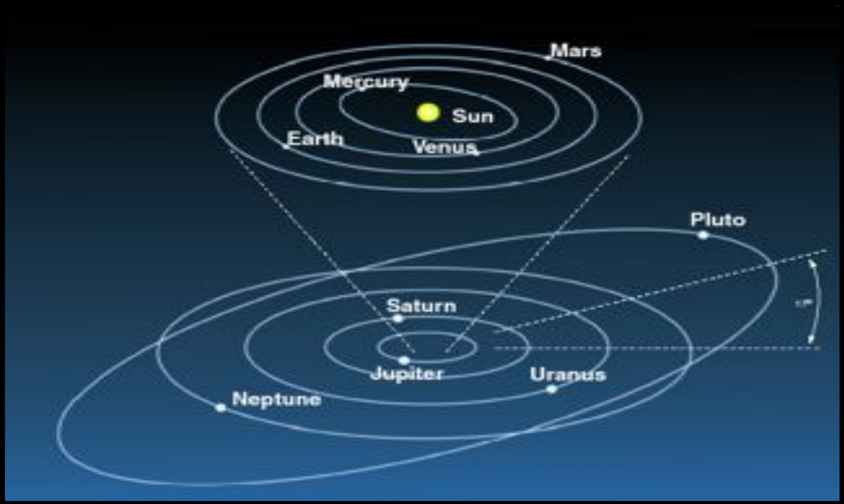


The laws of motion and gravity

Newton's Laws of motion

- ✓ First Law
  Every body continues at rest or in motion in a straight line unless acted upon by an outside force
- ✓ Second Law
  The acceleration of a body is proportional to the force acting on it (in the direction that the force is acting)
- ✓ Third Law
  For every action, there is an equal and opposite reaction





Gravitational Force

Universal law of gravitation

It's the popular notion that Newton "discovered" gravity and the story is that he did so when struck on the head by an apple while sleeping under a tree

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This is a direct descendant of the apple tree that was below Newton's room at Cambridge University

Gravitational Force

Scientific history in our backyard

In 1968, to commemorate the opening of the TRIUMF lab, cuttings from Newton's apple tree were planted on the south campus of UBC

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Gravitational Force

Scientific history in our backyard

In 1968, to commemorate the opening of the TRIUMF lab, cuttings from Newton's apple tree were planted on the south campus of UBC

This is a direct descendant of the apple tree that was below Newton's room at Cambridge University

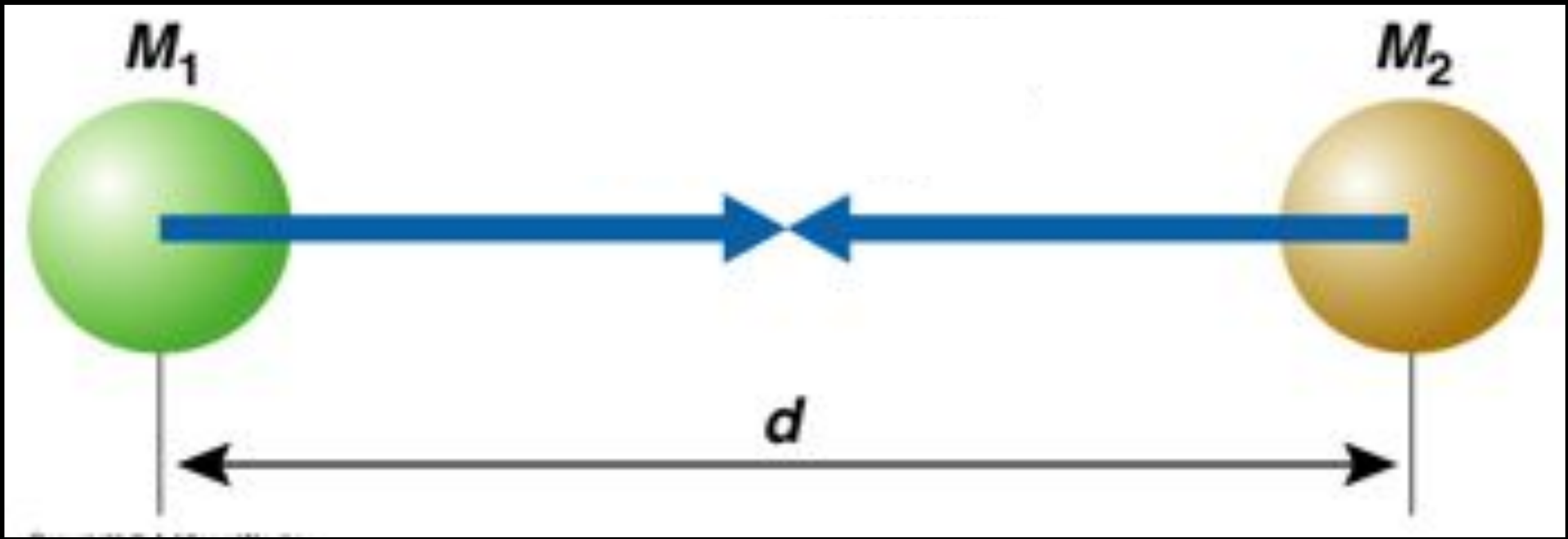
Those six trees bear fruit every year. If you nap under one, you may discover the next big thing in science

Cambridge
England

Vancouver
Canada

Gravitational Force

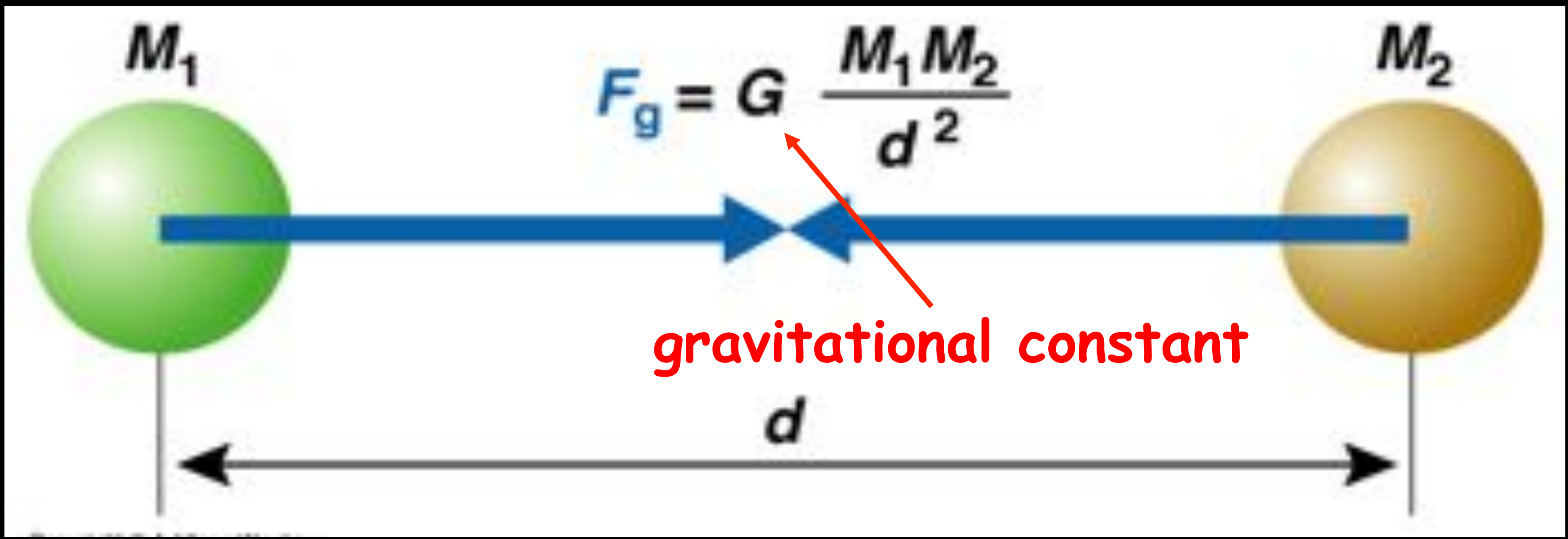
Universal law of gravitation



Between every two objects there is an attractive force which is directly proportional to the masses of the objects and inversely proportional to the square of the distance between the centres of the objects

Gravitational Force

Universal law of gravitation



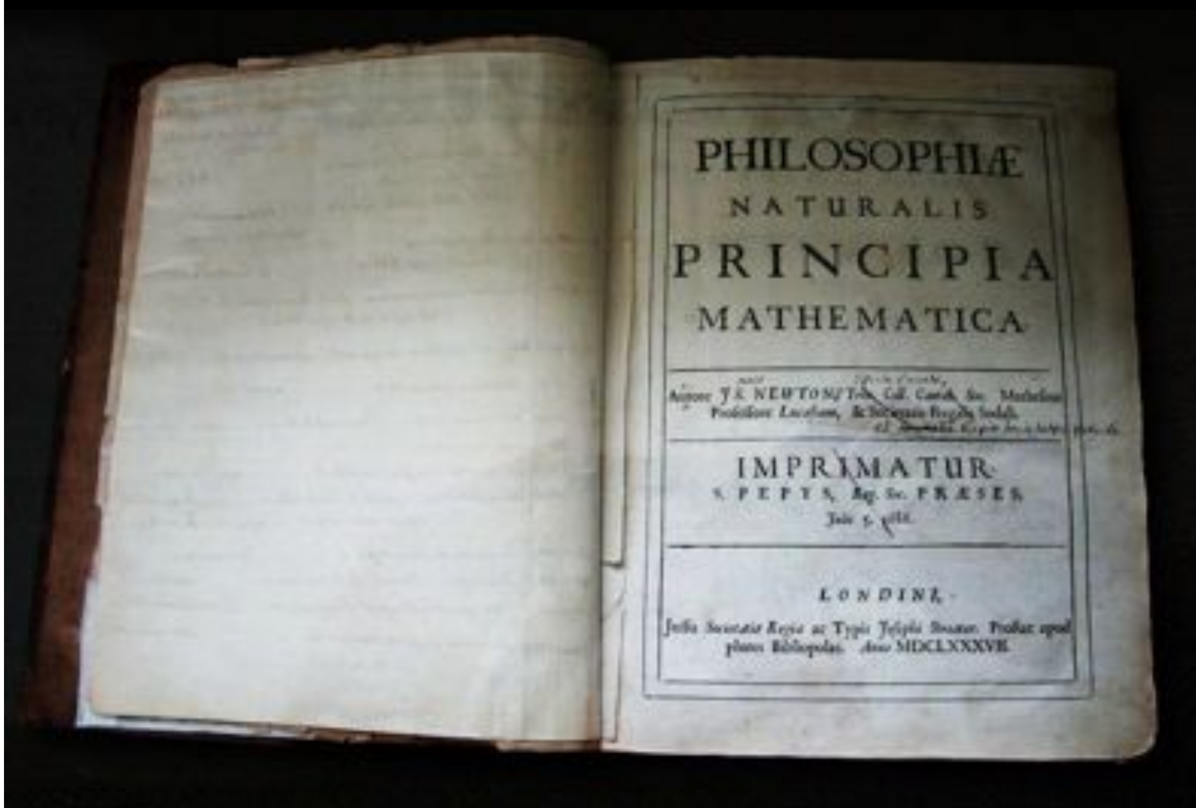
$$F_g = G \frac{M_1 M_2}{d^2}$$

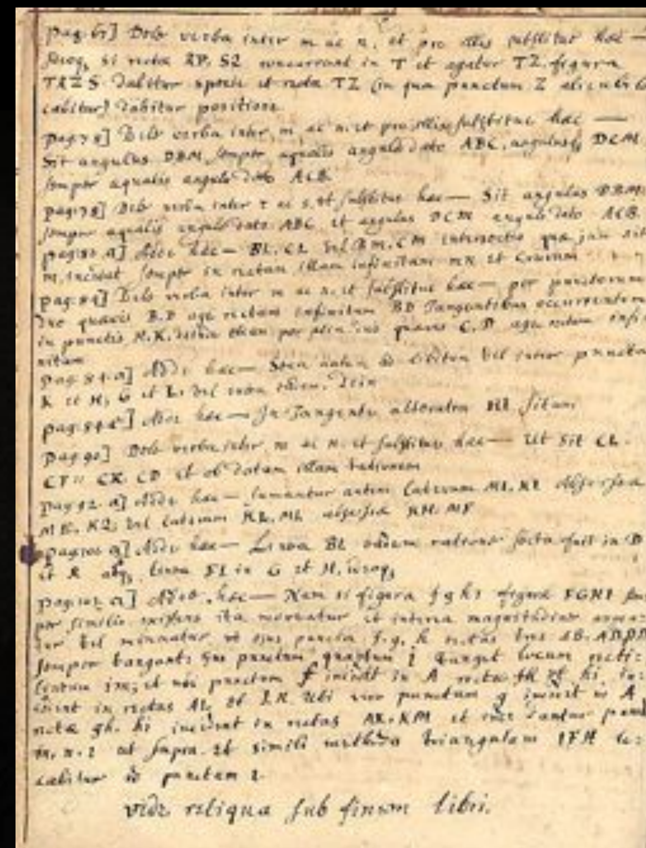
gravitational constant

$G = 6.67 \times 10^{-11}$ N m^2 / kg^2

Principia

The rule book for that law

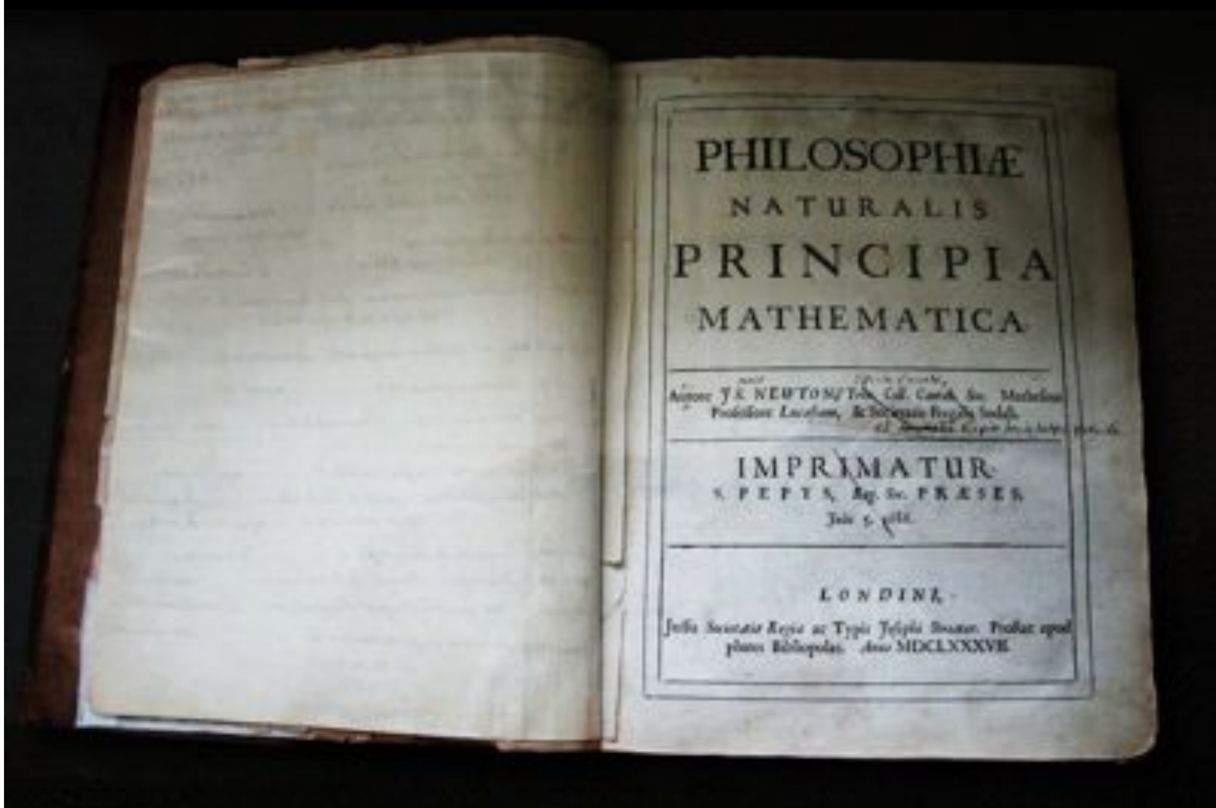


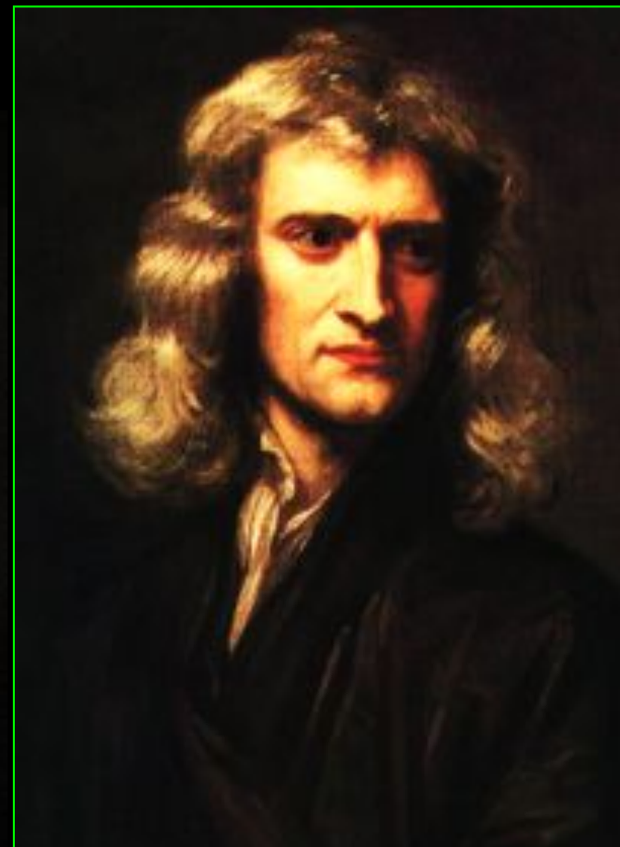


The laws of motion and gravity

My story began with this man …

Sir Isaac Newton (1643 – 1727)





The laws of motion and gravity

… <u>but the hero of my tale is this man</u>

Sir Edmond Halley (1656 – 1743)

The laws of motion and gravity

<u>He’s known people by most for this</u>

Sir Edmond Halley (1656 – 1743)

Halley’s Comet
(as seen in 1986)

The laws of motion and gravity

… but not for the right reason

Sir Edmond Halley (1656 – 1743)

Halley didn't discover this comet
but he proposed that comets
that had been seen every 76 years
in history were the same comet.

He predicted that comet's return.

Halley's Comet
(as seen in 1986)

The laws of motion and gravity

A legacy of cleverness in the sky

Sir Edmond Halley (1656 – 1743)

Halley didn't discover this comet
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in history were the same comet.

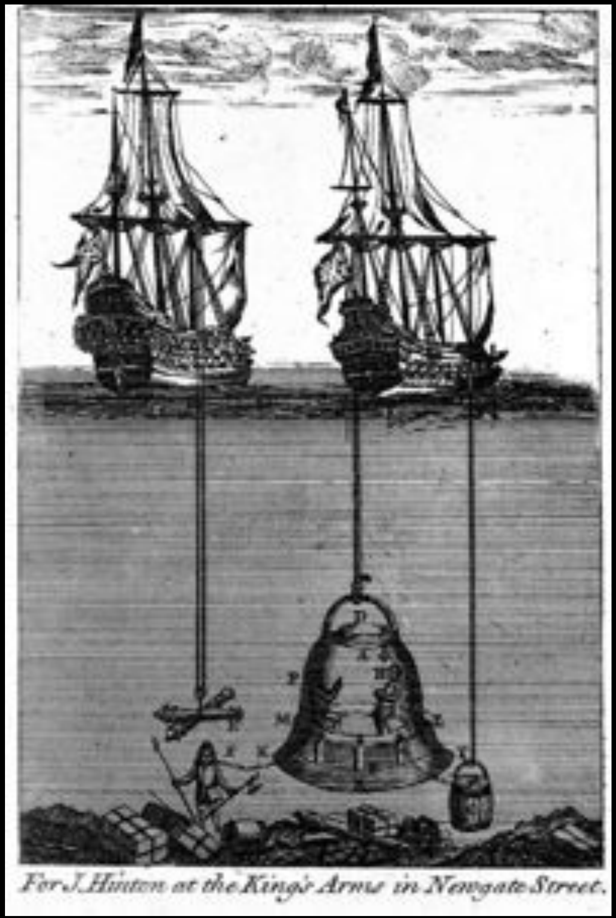
He predicted that comet's return.

After it was seen in the sky
when and where he predicted
(but after his death)
the comet was named after him.

A scientist adventurer

Getting underneath the surface of a problem

Sir Edmond Halley (1656 – 1743)



also designed, built and tested in 1690 the forerunner of the modern *diving bell*

He and five friends used it to stay for 90 minutes beneath the River Thames at a depth of 60 feet

A scientist adventurer

Wandering around the globe

Sir Edmond Halley (1656 – 1743) also commanded the sailing ship *Paramour* to chart the wander of the Earth's north magnetic pole

A scientist adventurer

Wandering around the globe

Sir Edmond Halley (1656 – 1743) also commanded the sailing ship *Paramour* to chart the wander of the Earth's north magnetic pole

While sailing the ocean Halley learned to "curse like a sea dog"

A scientist adventurer

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Pirate Captain Jack Sparrow's family crest

A scientist adventurer

Wandering around the globe

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Physics Captain Isaac Newton's family crest

A scientist adventurer

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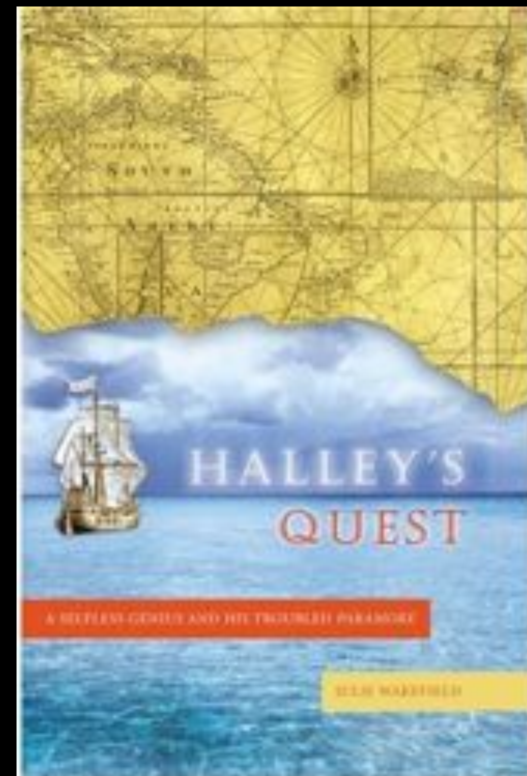

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A scientist adventurer

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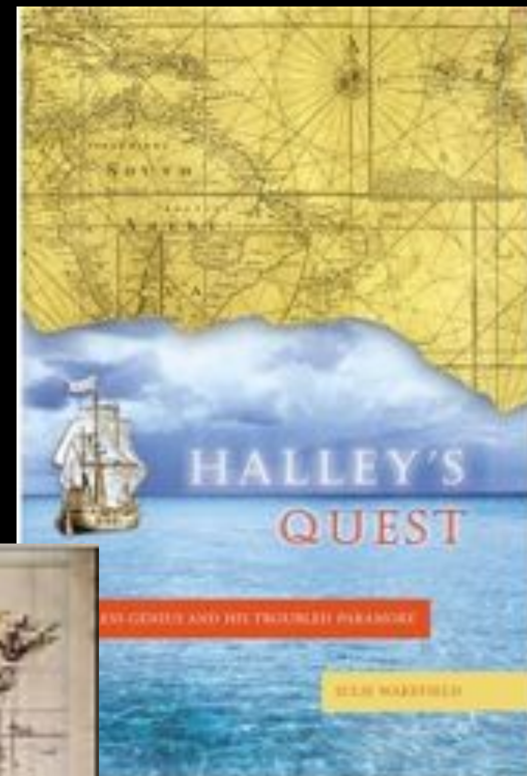
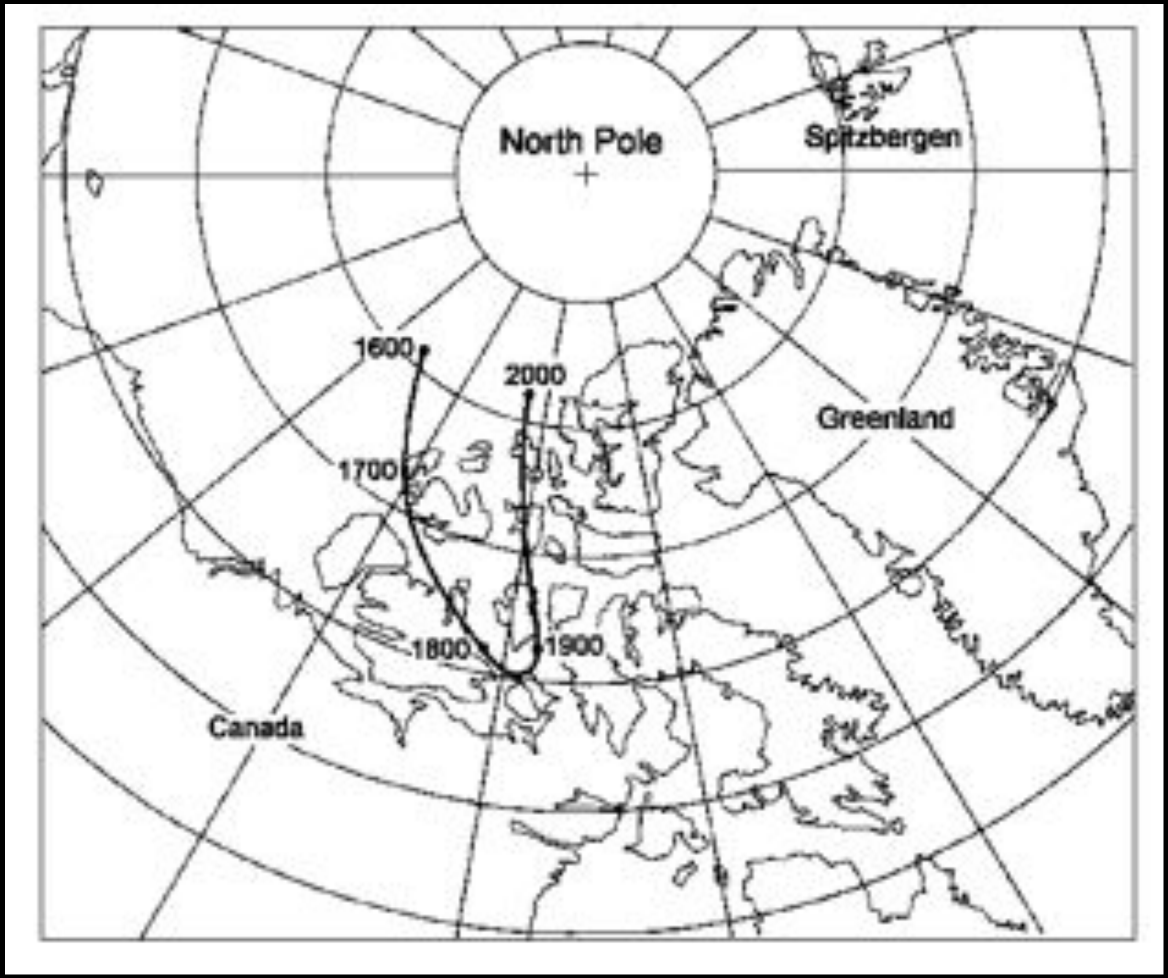
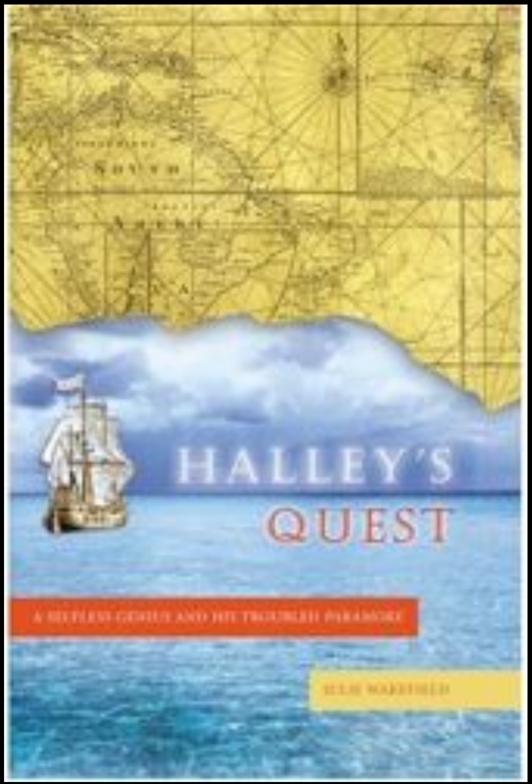


Edmund Halley's 1701 map of the known magnetic variations of the world.

A scientist adventurer

Wandering around the globe





A scientist adventurer

When Halley wasn't wandering, he was …

A scientist's inspiration

"Hooke"d on a problem

Halley, architect *Christopher Wren* and physicist *Robert Hooke*

debated in January 1684 and Hooke claimed to have derived *Kepler's Laws of planetary motion*

Kepler's Three Laws

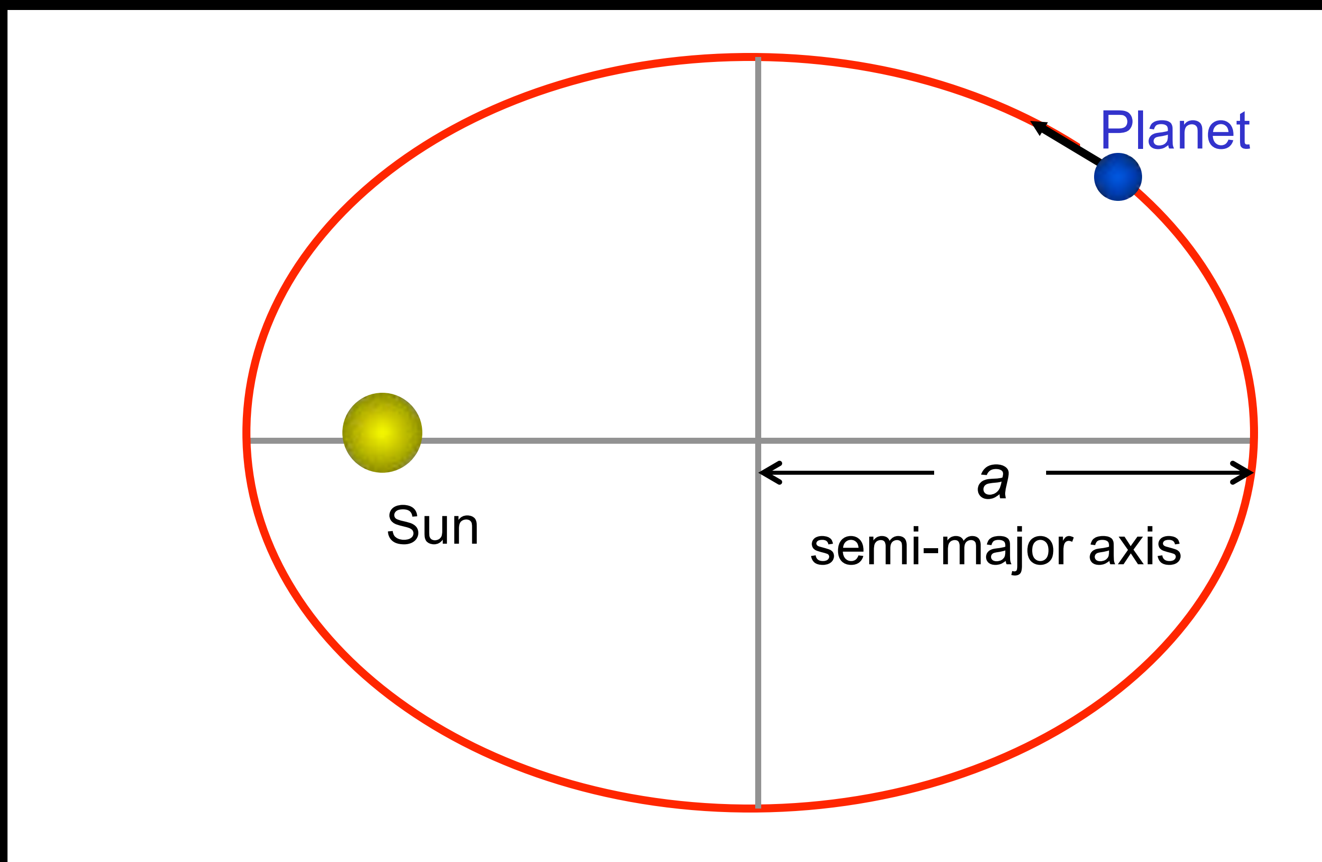
Principles of planetary motion

Johannes Kepler,
a German mathematician,
took two decades
to correctly interpret
Danish astronomer
Tycho Brahe's
measurements of
the positions of
the planet Mars in the sky

His *three laws of planetary motion*
are still used today

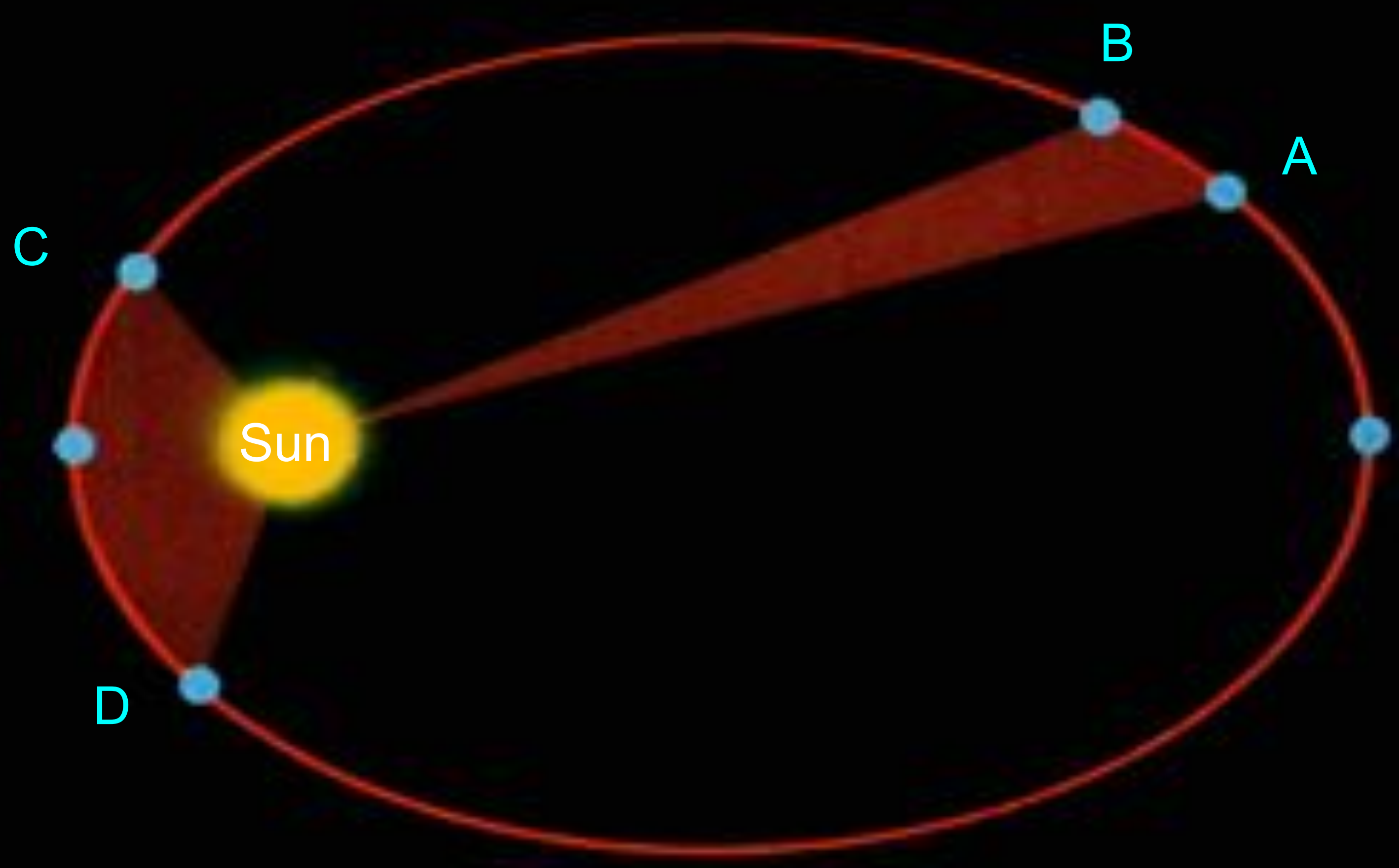
Kepler's First Law

Planets' orbits are ellipses with the Sun at one focus



Kepler's Second Law

A line joining the planet and the Sun sweeps out equal areas in equal times



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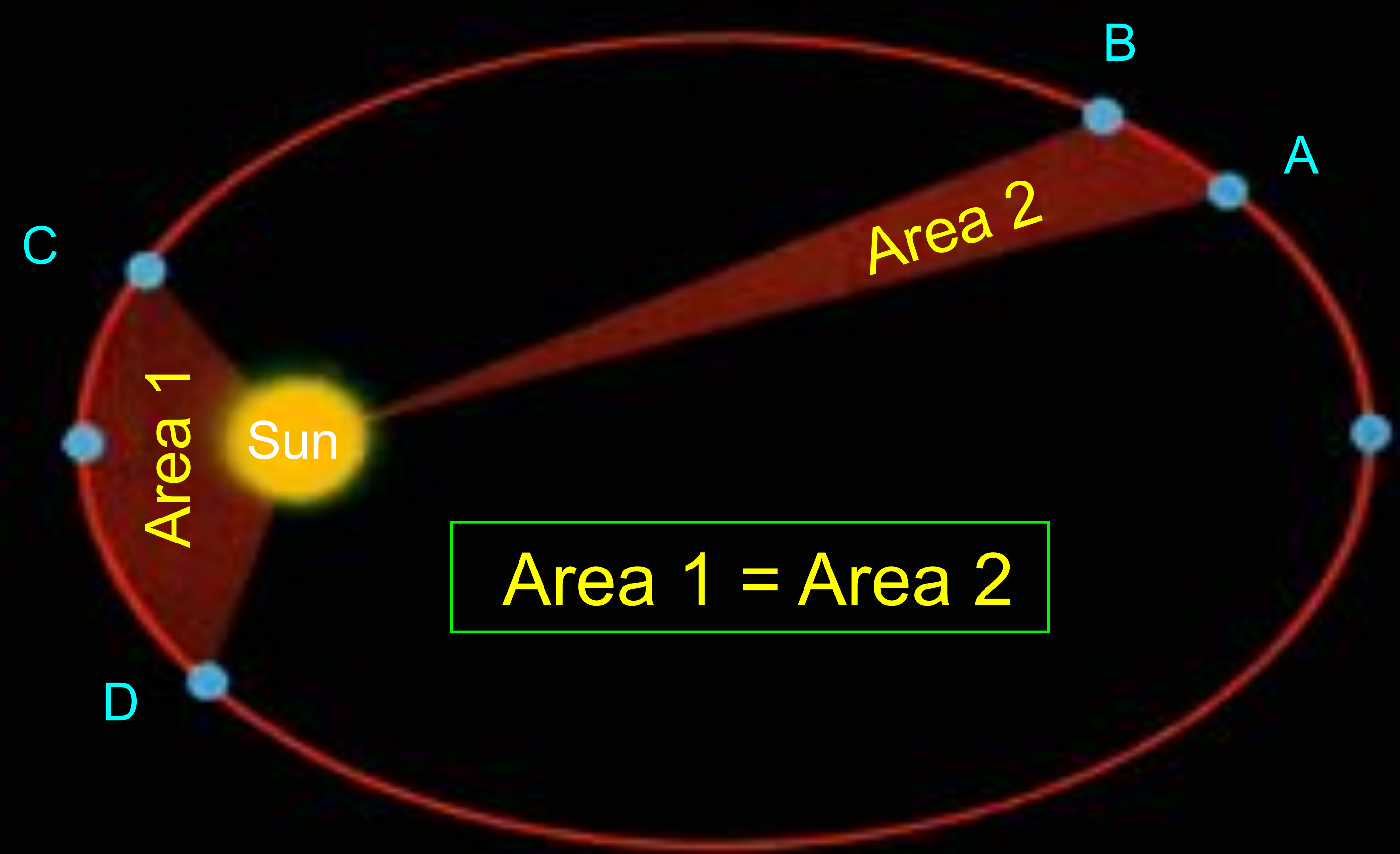

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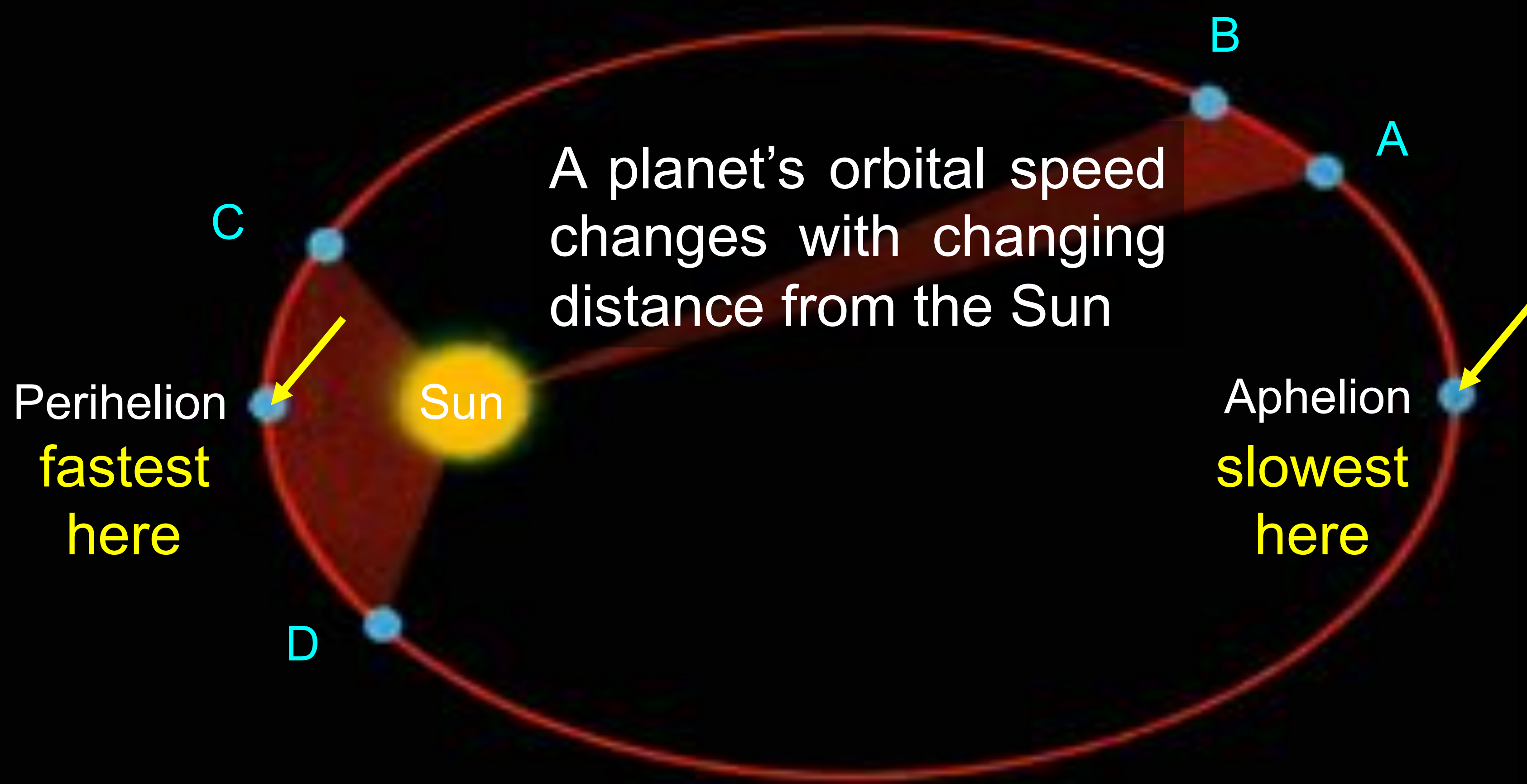


Kepler's Third Law

The (orbital period)^2 is proportional to (semi-major axis)^3

The planets Kepler knew

	semi-major axis *a* (AU)	period P (years)	a^3	P^2
Mercury	***0.39***	***0.24***	***0.0593***	***0.0576***
Venus	***0.72***	***0.62***	***0.3732***	***0.3844***
Earth	***1.00***	***1.00***	***1.000***	***1.000***
Mars	***1.52***	***1.88***	***3.5118***	***3.5344***
Jupiter	***5.20***	***11.86***	***140.61***	***140.66***
Saturn	***9.54***	***29.4***	***868.25***	***867.89***

Kepler's Third Law

The (orbital period)^2 is proportional to (semi-major axis)^3

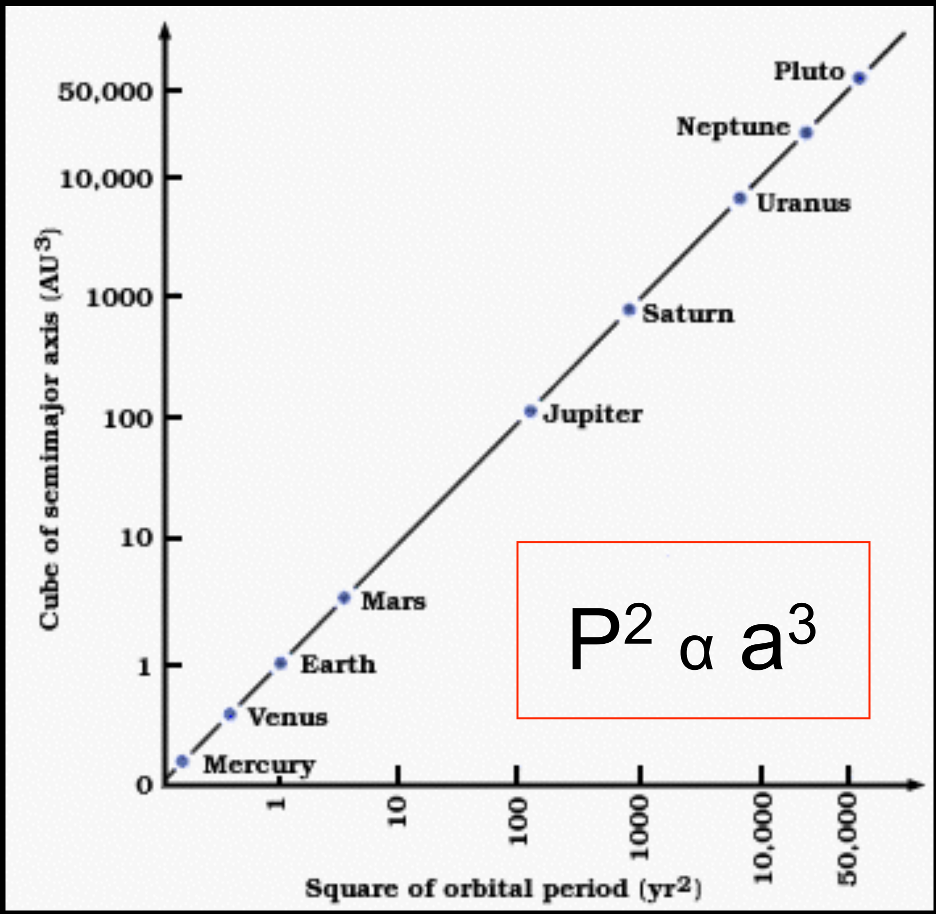
The planets we now know

		semi-major axis *a* (AU)	period P (years)	a^3	P^2
	Mercury	***0.39***	***0.24***	***0.0593***	***0.0576***
	Venus	***0.72***	***0.62***	***0.3732***	***0.3844***
	Earth	***1.00***	***1.00***	***1.000***	***1.000***
	Mars	***1.52***	***1.88***	***3.5118***	***3.5344***
Not a planet	*Asteroid belt*	***2.77***	***4.60***	***21.254***	***21.160***
	Jupiter	***5.20***	***11.86***	***140.61***	***140.66***
	Saturn	***9.54***	***29.4***	***868.25***	***867.89***
	Uranus	***19.19***	***84.07***	***7,066***	***7,068***
	Neptune	***30.06***	***164.80***	***27,162***	***27,159***
Not a planet	*Pluto*	***39.60***	***248.60***	***62,099***	***61,802***

Kepler's Third Law

The (orbital period)^2 is proportional to (semi-major axis)^3

If you know the orbital period of a planet in the Solar System you can use Kepler's 3rd Law to determine its distance from the Sun relative to Earth's distance (1 AU)



A scientist's inspiration

"Hooke"d on a problem

Halley, architect *Christopher Wren* and physicist *Robert Hooke*

talked in January 1684 and Hooke claimed to have derived Kepler's Laws of planetary motion

A scientist's inspiration

"Hooke"d on a problem

Hooke could not produce his general derivation and *Halley* was suspicious of the claim

This spurred him to raise the problem in August 1684 with his friend *Newton* who was inspired by Halley's interest and enthusiasm

A scientist's inspiration

"Hooke"d on a problem

Hooke could not produce his general derivation and *Halley* was suspicious of the claim

This spurred him to raise the problem in August 1684 with his friend *Newton* who was inspired by Halley's interest and enthusiasm

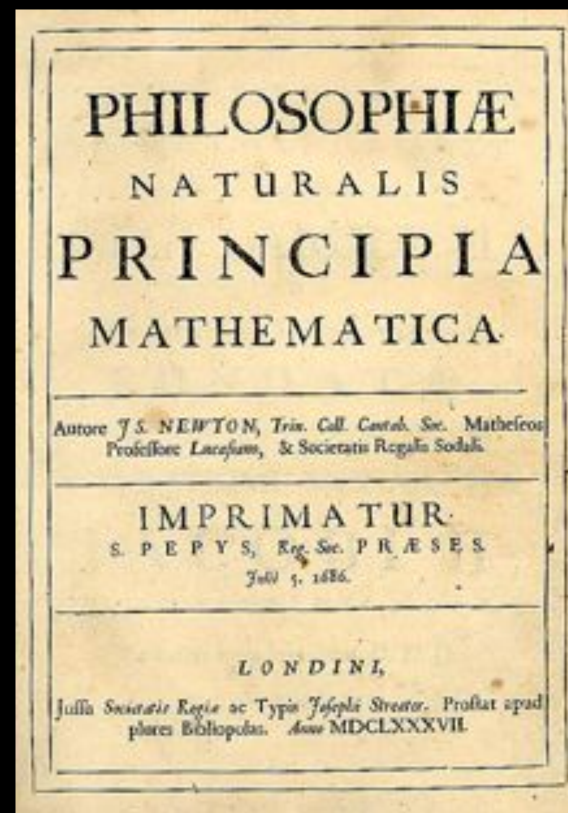
In November 1684, *Newton* presented *Halley* with a 9-page manuscript "*De moto corporum in gyrum*" ("Of the motions of a body in orbit") – Kepler's laws derived with an inverse-square force

A scientist's inspiration

“Hooke”d on a problem

Halley was impressed and pleaded with *Newton* to present more such work to the Royal Society

Newton was consumed by this and spent the next two years writing what would become *Philosophiæ Naturalis Principia Mathematica*



PHILOSOPHIÆ
NATURALIS
PRINCIPIA
MATHEMATICA.

Autore J S. NEWTON, Trin. Coll. Cantab. Soc. Matheseos Professore Lucasiano, & Societatis Regalis Sodali.

IMPRIMATUR.
S. PEPYS, Reg. Soc. PRÆSES.
Julii 5. 1686.

LONDINI,
Jussu Societatis Regiæ ac Typis Josephi Streater. Prostat apud plures Bibliopolas. Anno MDCLXXXVII.

A scientist's inspiration

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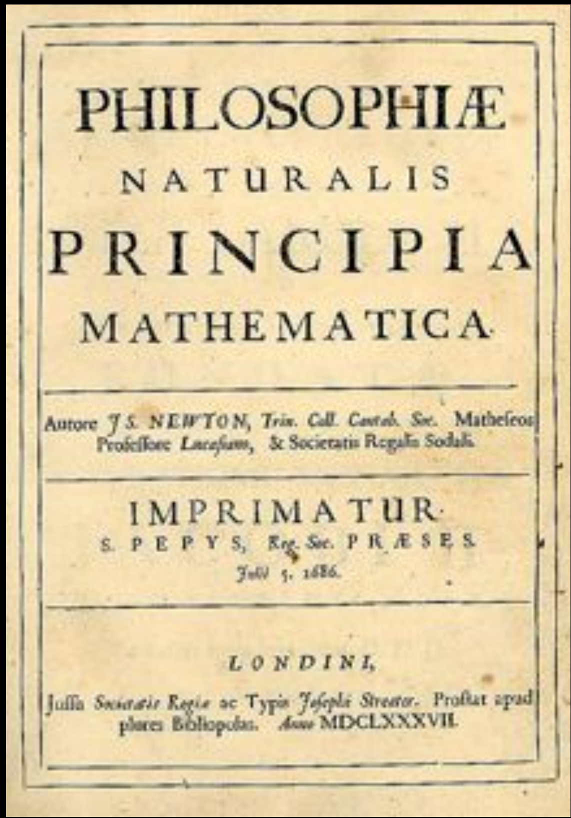
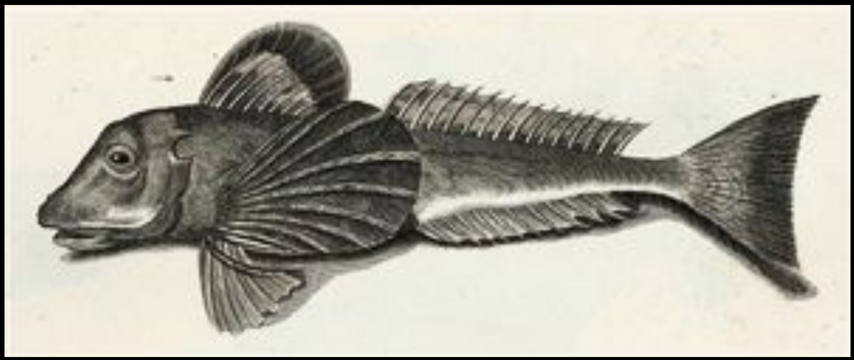


But this is NOT the end of the story

A scientist's nightmare

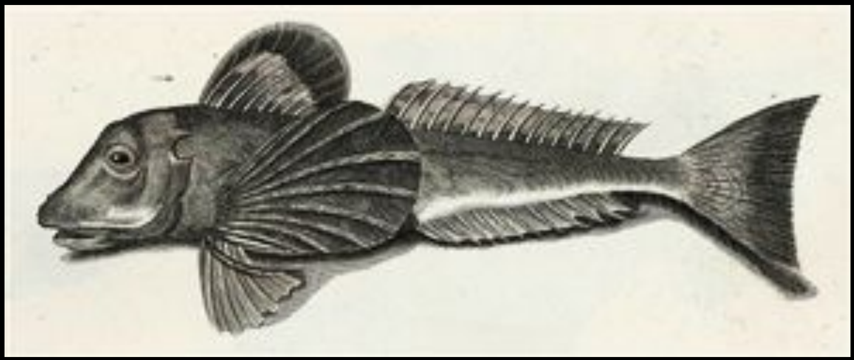
Hooked on a fish



This is a red gurnard as depicted in *Francis Willughby's* *De Historia Piscium* ("The History of Fishes")

A scientist's nightmare

Hooked on a fish



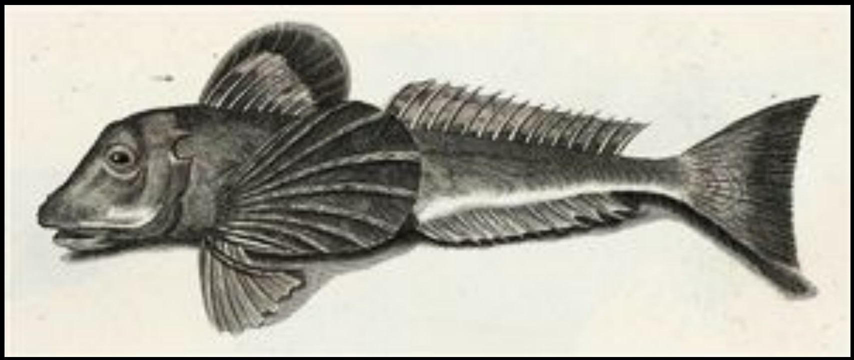
This is a red gurnard as depicted in *Francis Willughby's* *De Historia Piscium* ("The History of Fishes")

The Royal Society consumed almost their entire budget in 1686 to publish "The History of Fishes" which was a commercial disaster

They had no money left to publish *Principia*

A scientist's saviour

Off the hook



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Halley stepped in and underwrote the publication of the first edition

5 July 1687

What about my original question?

What's the connection between *gravity* and *life insurance*?

insurance salesman

The Halley connection

Halley was a very clever scientist !!!

Sir Edmond Halley
was the 'inventor' of *life insurance*

insurance salesman

The Halley connection

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Age. Curt.	Persons.	Age. Curt.	Persons.	Age. Curt.	Persons.	Age. Curt.	Persons.	Age. Curt.	Persons.	Age. Curt.	Persons.
1	1000	8	680	15	628	22	586	29	539	36	481
2	855	9	670	16	622	23	579	30	531	37	472
3	798	10	661	17	616	24	573	31	523	38	463
4	760	11	653	18	610	25	567	32	515	39	454
5	732	12	646	19	604	26	560	33	507	40	445
6	710	13	640	20	598	27	553	34	499	41	436
7	692	14	634	21	592	28	546	35	490	42	427
Age. Curt.	Persons.	Age. Curt.	Persons.	Age. Curt.	Persons.	Age. Curt.	Persons.	Age. Curt.	Persons.	Age. Curt.	Persons.
43	417	50	346	57	272	64	202	71	131	78	58
44	407	51	335	58	262	65	192	72	120	79	49
45	397	52	324	59	252	66	182	73	109	80	41
46	387	53	313	60	242	67	172	74	98	81	34
47	377	54	302	61	232	68	162	75	88	82	28
48	367	55	292	62	222	69	152	76	78	83	23
49	357	56	282	63	212	70	142	77	68	84	20

Age.	Persons.
7	5547
14	4584
21	4270
28	3964
35	3604
42	3178
49	2709
56	2194
63	1694
70	1204
77	692
84	253
100	107
	34000
	Sum Total.

The first actuarial table

The Halley connection

Halley was a <u>very</u> clever scientist !!!

Sir Edmond Halley
was the 'inventor' of *life insurance*

Age. Curt.	Per-sons.	Age. Curt.	Per-sons.	Age. Curt.	Per-sons.	Age. Curt.	Per-sons.	Age. Curt.	Per-sons.	Age. Curt.	Per-sons.
1	1000	8	680	15	628	22	586	29	539	36	481
2	855	9	670	16	622	23	579	30	531	37	472
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4	760	11	653	18	610	25	567	32	515	39	454
5	732	12	646	19	604	26	560	33	507	40	445
6	710	13	640	20	598	27	553	34	499	41	436
7	692	14	634	21	592	28	546	35	490	42	427
Age. Curt.	Per-sons.	Age. Curt.	Per-sons.	Age. Curt.	Per-sons.	Age. Curt.	Per-sons.	Age. Curt.	Per-sons.	Age. Curt.	Per-sons.
43	417	50	346	57	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

Age.	Persons.
7	5547
14	4584
21	4270
28	3964
35	3604
42	3178
49	2709
56	2194
63	1694
70	1204

From "An estimate of the degrees of the mortality of mankind, drawn from curious tables of the births and funerals at the city of Breslaw; with an attempt to ascertain the price of annuities upon lives" (1693)

The first actuarial table

A Physics Trivial Pursuit question?

Q. What's the connection between *gravity* and *life insurance*?

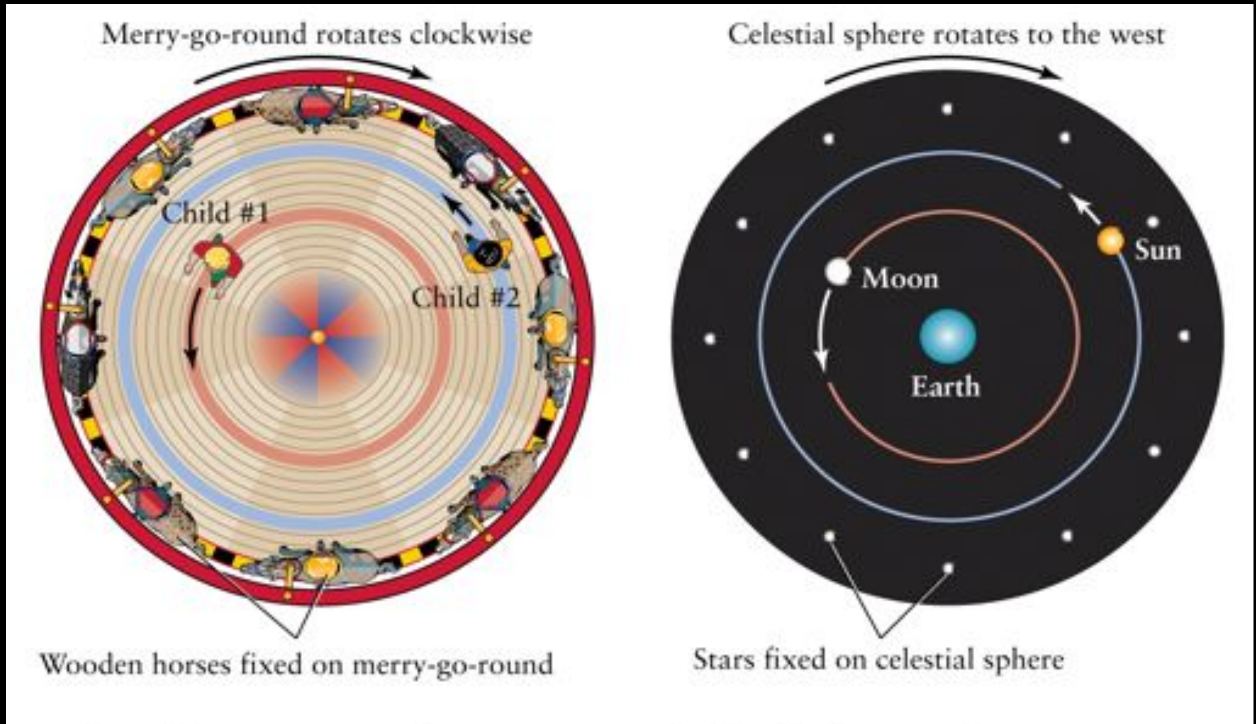
A. Halley, friend and funder of Newton, and a clever scientist in his own right

A question of morality?

Q. What would *you* do to possess the most exquisite scientific data on Earth?

Geocentric Universe

To answer this, we must go back in history …



a A rotating merry-go-round

b The Greek geocentric cosmogony

In ancient times, the Sun, Moon and stars were thought to be fixed on different transparent "*celestial spheres*" all revolving at different rates around the unmoving Earth at the centre

Torontocentric Universe

Geocentric Universe

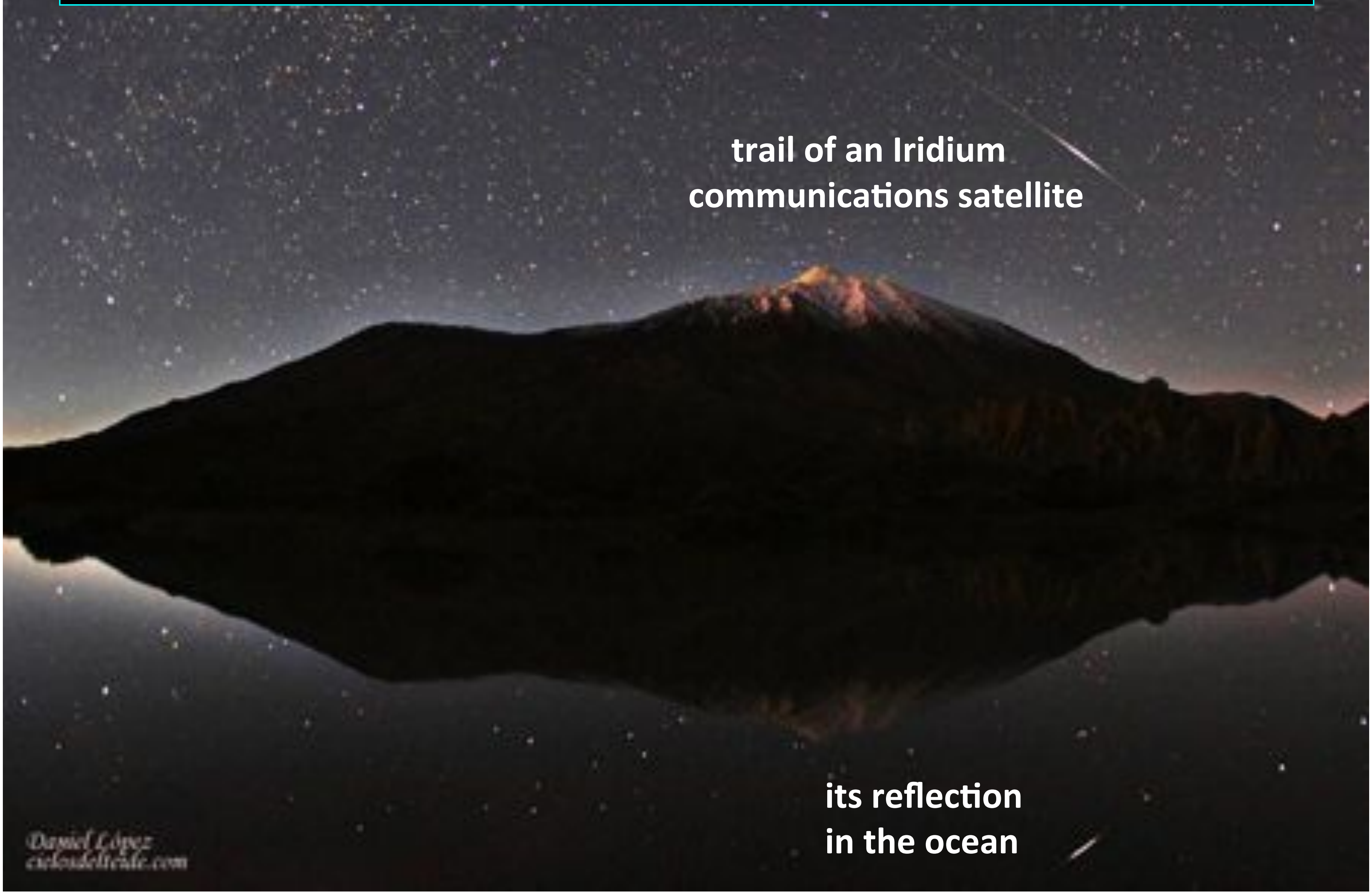
The ancient Greeks put the stars and planets and the Sun and Moon on different spheres centred on us

The night sky over the Tiede volcano

The night sky over the Tiede volcano

and under

The night sky over the Tiede volcano



Diurnal circles over the Tiede volcano

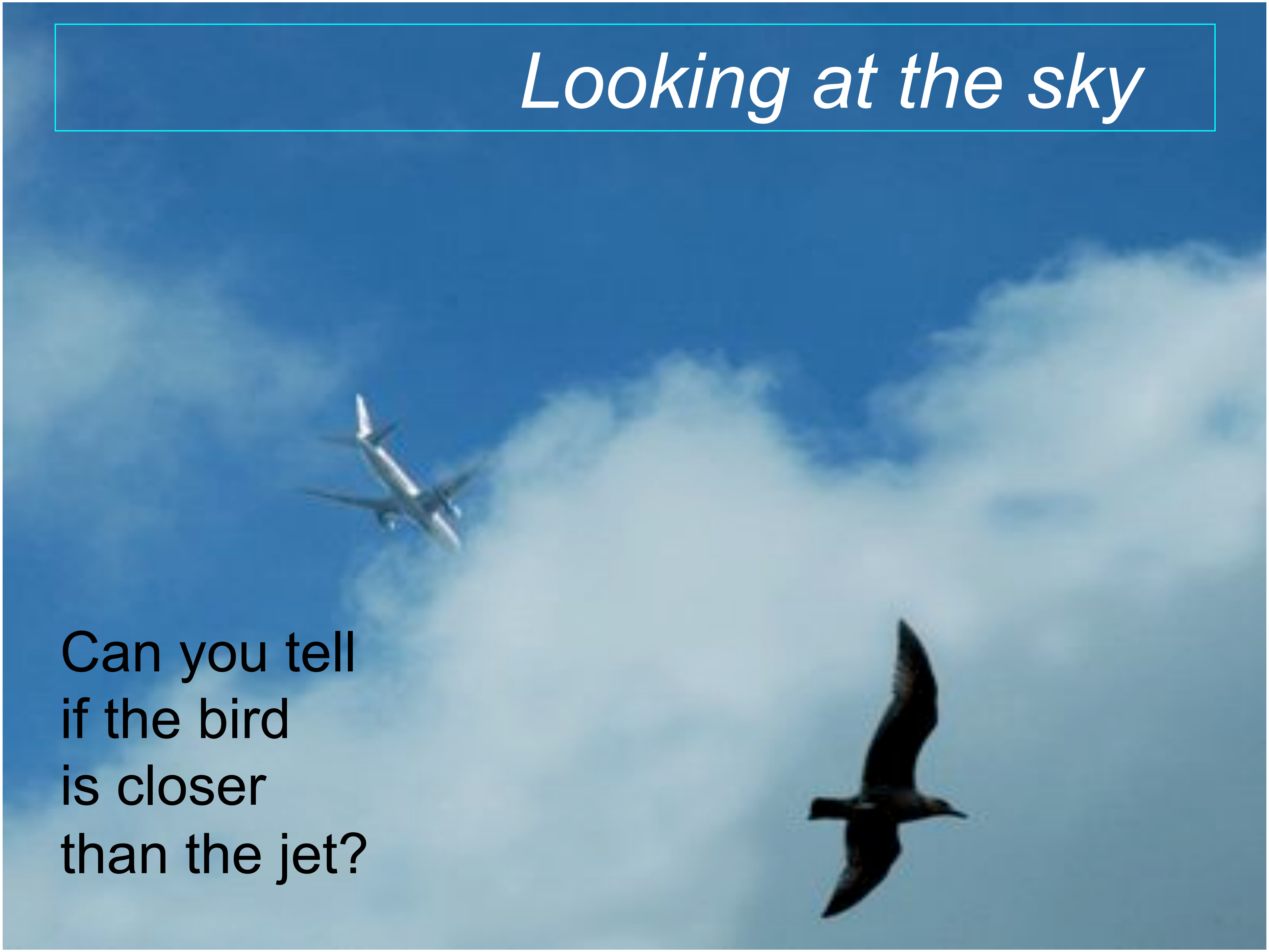
a 4.5-hour exposure revealing star trails and their reflections

Looking at the sky

Looking at the sky

Can you tell
if some stars
are closer
than others?

Looking at the sky



Can you tell
if the bird
is closer
than the jet?

Looking at the sky

You know that the bird
is closer than the jet

Unless the bird
happens to be

**Rod
an!**

Looking at the sky

Or this happens to be the jet

Looking at the sky

What you see

View from the side

Looking at the sky

Can you tell if some stars are closer than others?

No


It looks to us like all the stars are projected on a big sphere centred on us, like a planetarium dome
(where this picture was taken)

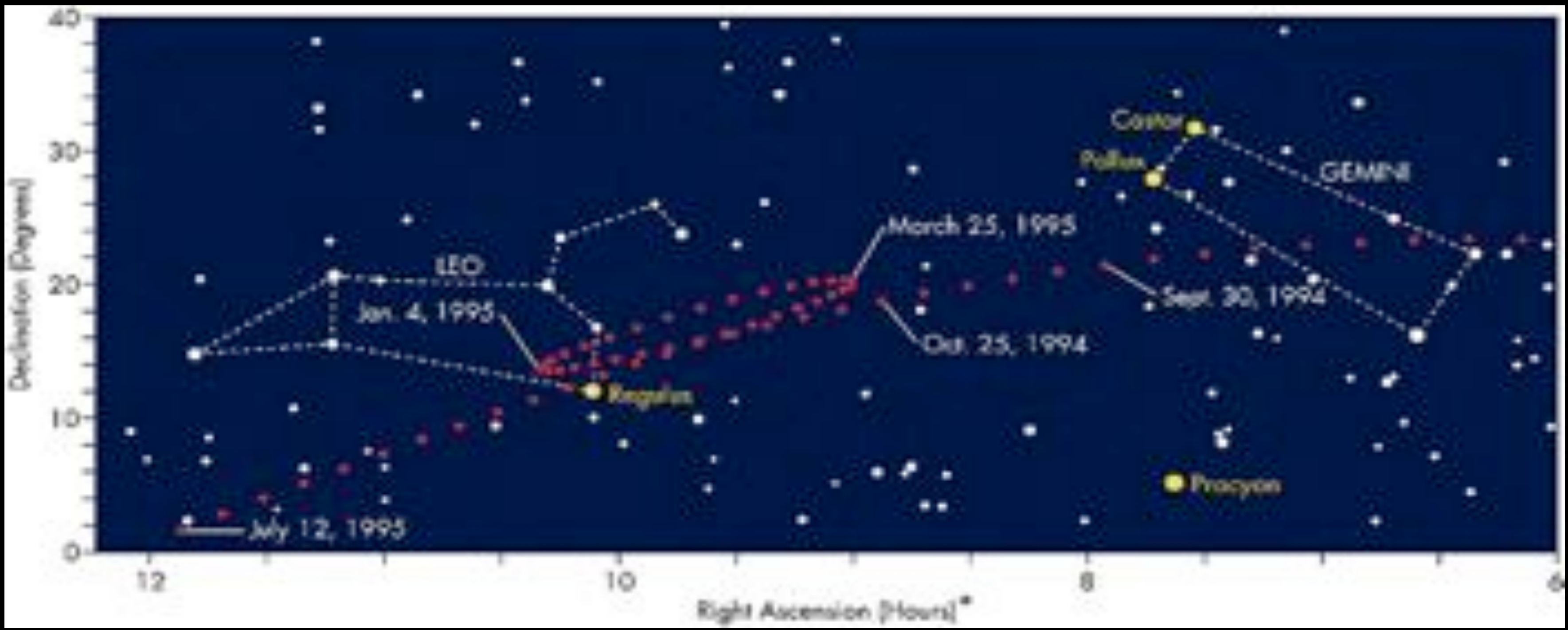
Geocentric Universe

The Ptolemaic model

Claudius Ptolemy – living in Rome near 100 AD – developed a geocentric model that could predict the positions of planets in the sky over time

Geocentric Universe

Mars moving "backward"

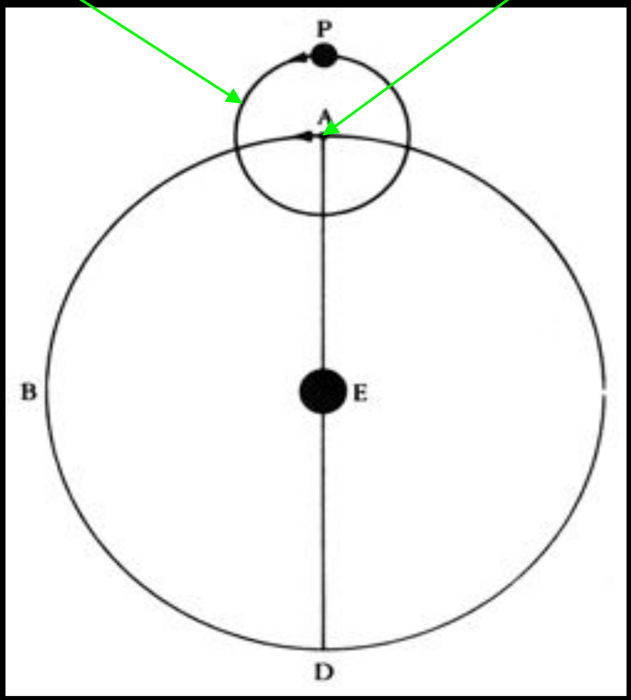


The model could also explain why planets sometimes move backward in the sky, in what are called *retrograde loops*

Geocentric Universe

The Ptolemaic model

Epicycle and *deferent*



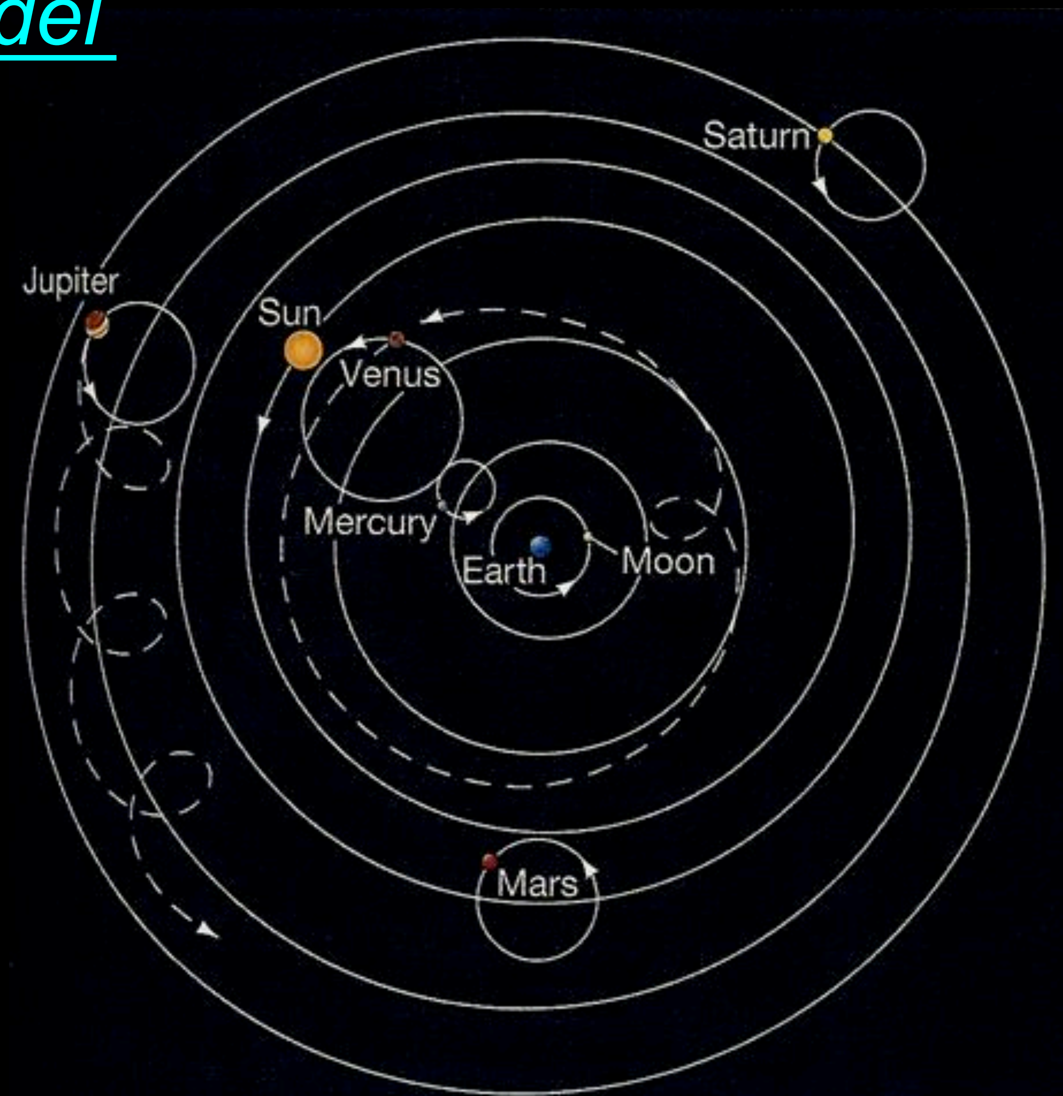
reproduced
retrograde motion

Geocentric Universe

Epicycles and retrograde loops

Geocentric Universe

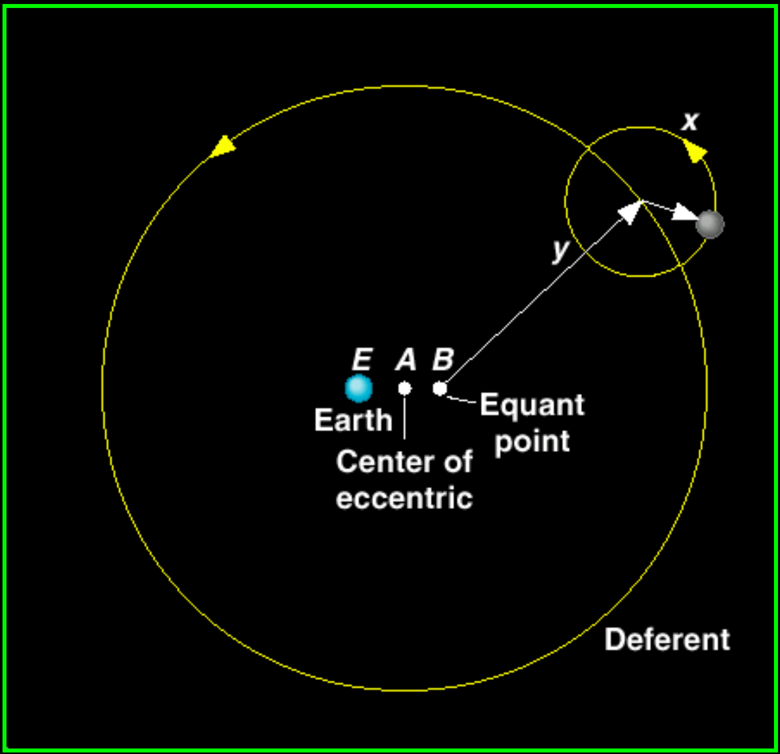
The Ptolemaic model



Geocentric Universe

The Ptolemaic model got the apparent motions right!

up to accuracy of the observations at the time, about 10 arcmin ~ 1/6º

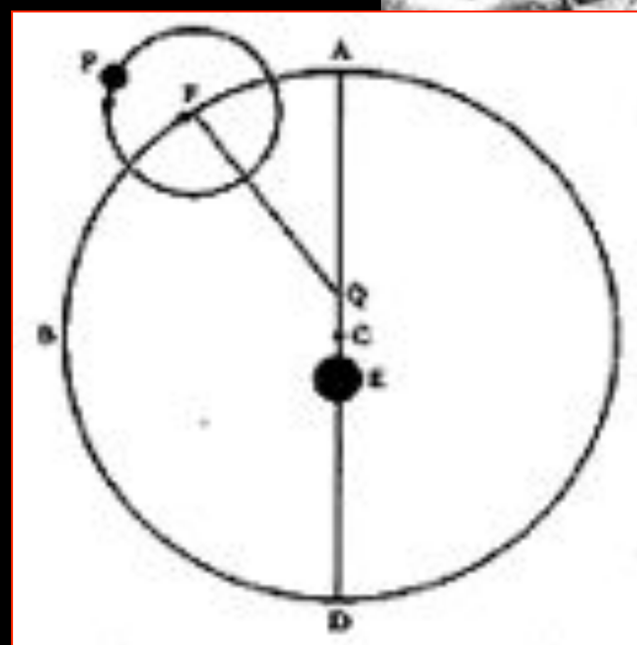


A planetarium projector is essentially a mechanical version of a Ptolemaic model

Geocentric Universe

The Ptolemaic millennium

Ptolemy's major written work was renamed the Almagest ("the greatest compilation") by Arab scholars who preserved the Greek scientific knowledge during the "Dark Ages"

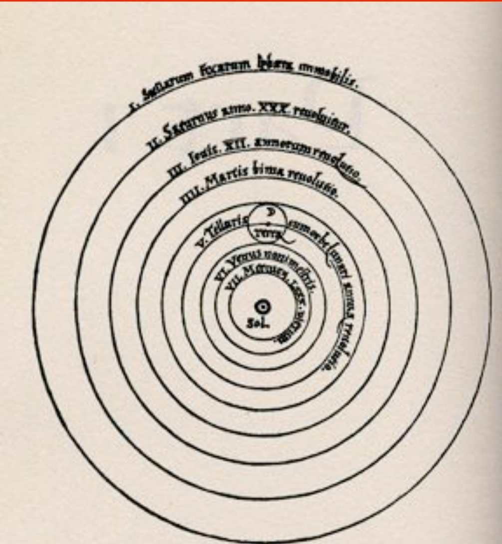


Ptolemy's model of the Universe held sway for about <u>1500 years</u>!

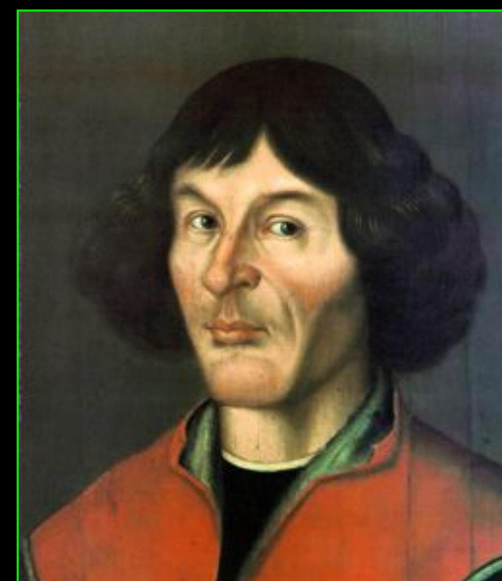
Heliocentric Solar System

The beginning of the Copernican revolution

Polish astronomer Nikolai Copernicus (1473 – 1543) proposed that the Sun is at the centre of the Solar System and the planets, including Earth, orbit the Sun in circles



The Sun-centered model of the cosmos. From Copernicus, *De Revolutionibus*, 1543.
Source: *Wolbach Library, Harvard University.*



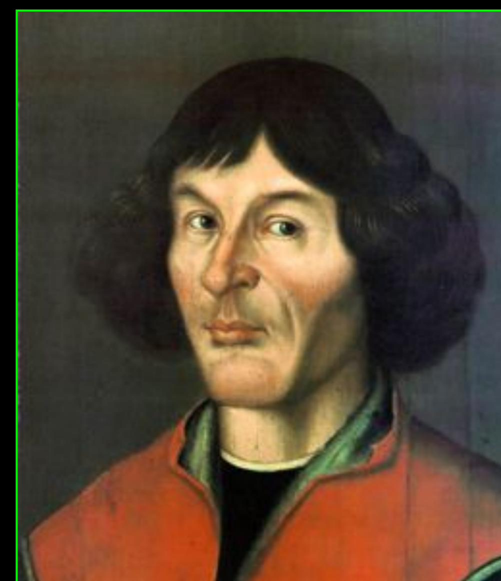

Jan Matejko

Heliocentric Solar System

The beginning of the Copernican revolution

Polish astronomer Nikolai Copernicus (1473 – 1543) proposed that the Sun is at the centre of the Solar System and the planets, including Earth, orbit the Sun in circles

Copernicus' book *De Revolutionibus* was published in 1543 after he died



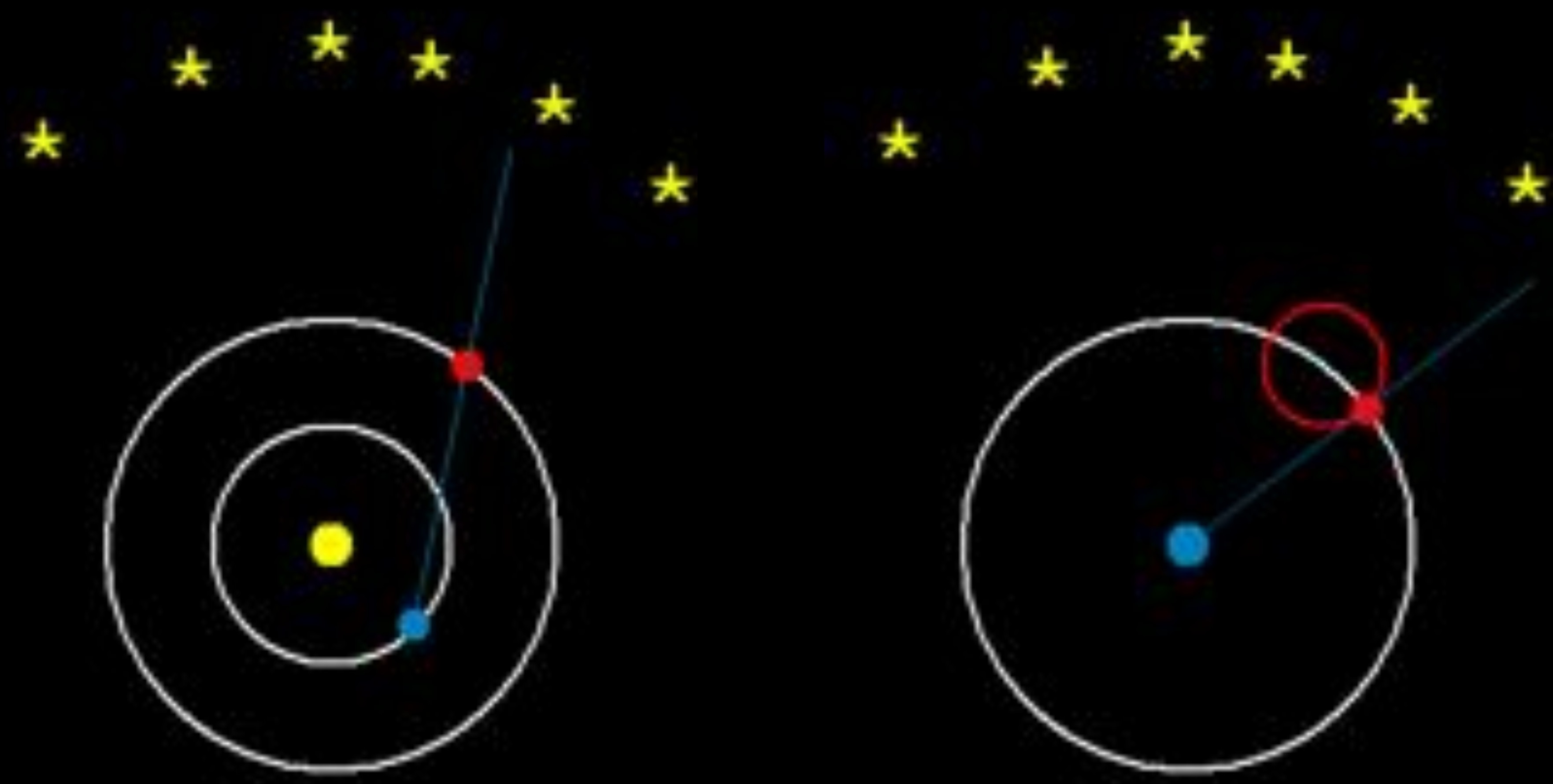
Heliocentric Solar System

Copernicus' model explains retrograde motion

As Earth and Mars revolve around the Sun at different speeds, Earth "laps" Mars, making it appear that Mars is going backwards briefly

Heliocentric Solar System

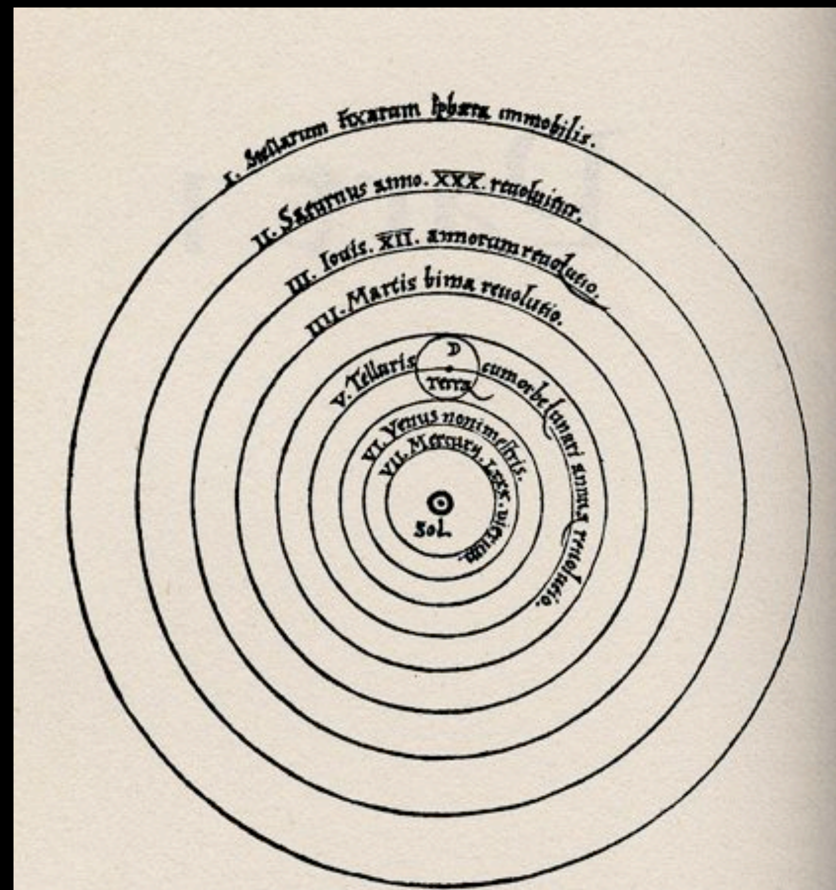
Copernicus' model explains retrograde motion more simply than Ptolemy's epicycles



Heliocentric Solar System

Copernicus' model wasn't accepted right away

Like Ptolemy and all other astronomers up to that time, Copernicus believed that celestial bodies moved in perfect circles. To explain the changing rates of the planets' motions with circular orbits, the Copernican model also required epicycles



The Sun-centered model of the cosmos. From Copernicus, *De Revolutionibus*, 1543.
Source: *Wolbach Library, Harvard University.*

Heliocentric Solar System

Understanding the true motions of planets

Danish astronomer *Tycho Brahe* was the best observer of stellar and planetary motions before the onset of telescopes

He built an observatory on the island of Hven: *Uraniborg* (*"Sky Castle"*)

Heliocentric Solar System

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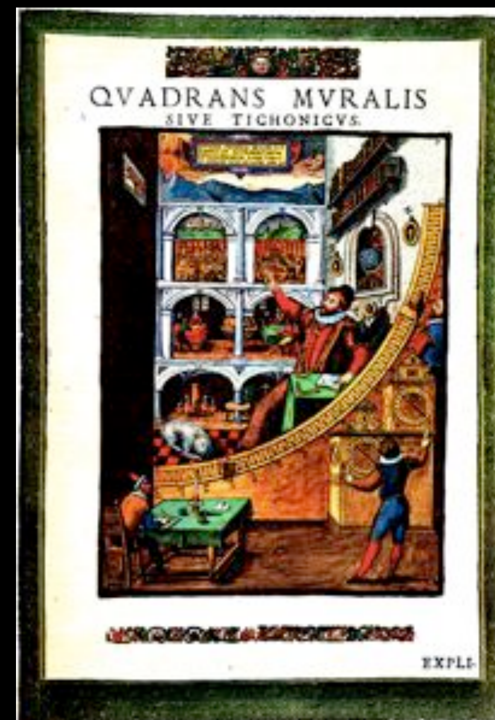

He built an observatory on the island of Hven: *Uraniborg ("Sky Castle")*

With no telescopes but with giant quadrants, Tycho Brahe measured planetary positions to an accuracy of *1 arcminute*

Heliocentric Solar System

Understanding the true motions of planets

Danish astronomer *Tycho Brahe* was the best observer of stellar and planetary motions before the onset of telescopes

He was also a *party animal*

Heliocentric Solar System

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Danish astronomer *Tycho Brahe* was the best observer of stellar and planetary motions before the onset of telescopes

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- ✓ *lost his nose* in a sword duel as a young man

Annals of Improbable Research, Vol. 10 (July/August 2004):6-7 (2004)

The Search for Tycho Brahe's Nose

by Mark Benecke, Forensic Biologist
Cologne, Germany

Astronomer Tygo Brahe (born 1546, died 1601; Latinized name Tycho Brahe) was not just an early geek. When he was exhumed in 1901 to celebrate the three hundredth anniversary of his death (and also to restore his grave), many people many people were eager to get a look at the famous metal insert that had been substituted the Brahe's birth nose.

Figure 1: Brahe with his damaged nose as it may really have appeared.

The Coming of the Nose

In 1572, as a student at the University of Copenhagen, Brahe observed a very bright star. He proved that it was a supernova located outside our solar system. Brahe's later observations of the orbits of Cassiopeia and of a comet made clear that those objects, too, were located more distantly than our moon. All this meant that – contrary to what many people believed – the heavens were changeable, not immutable as Aristotle had long ago postulated. Still, Brahe avoided painting a heliocentric view of the universe; he described the earth, rather than the sun, as being at the center of all things heavenly.

To take up his studies, Danish student Tygo had moved from Copenhagen University to the German cities of Leipzig, Wittenberg and Rostock. There, he developed an interest in alchemy and astronomy. He soon become a successful astronomer. In 1572, he observed the new star Cassiopeia and in 1574, he became a lecturer for astronomy in Copenhagen. Shortly after that, he took up an invitation by Prussian Kaiser Friedrich II to set up the finest astronomical observatory of its time, the "Uraniborg," on the island of Hven in the Sont near Copenhagen. From 1599 on, Brahe worked in Prague. In 1600, the German astronomer Johannes Kepler joined him. Kepler calculated planetary orbits – basing his calculations on Brahe's meticulous observations, which Brahe had performed without a telescope.

The Going of the Nose

Tyco Brahe's nose got lost, quite early, in a student fight. On December 10, 1566, Tycho and the Danish blue blood Manderup Parsbjerg were guests at an engagement party at Prof. Bachmeister in Rostock. The party included a ball, but the festive environment did not keep the two men from starting an argument that went on even over the Christmas period. On December 29, they finished the matter with a rapier duel. During the duel, which started at 7 p.m. in total darkness, a large portion of the nose of Brahe was cut off by his opponent. It was the most famous cut in science, if not the unkindest.

The Second Coming of the Nose

In those times in Germany (and also in Austria), it was socially okay – and even more than okay – to proudly show the signs of a duel (facial scars and other such marks of distinction). These signified that a man would stand up for his personal honor. However, to cover the – in this case extreme and unusual – disfigurement, Tycho ordered a substitute nose, made from a mixture of silver and gold. This was unusual, because in those days when someone lost a nose in that part of Europe, the replacement, if he or she were fortunate enough to be able to obtain one, was typically made of wax. (This was not as wildly unusual as it may sound to modern ears – it was not uncommon for people who suffered from lupus to lose their noses and attempt to obtain replacements.)

One of Brahe's pupils, Willem Janszoon Blaeu (the name was also spelled Wilhelm Janszoon Blaeu), who lived with Brahe for two years on the island of Hven, remembered that Brahe would always carry an ointment which he used on his nose. Aye, there's the rub – a nasty prize to pay for a hot-blooded fight!

Figure 2: Brahe with his damaged nose, a little beautified – but this time with the real form of his eyes. "This portrait is from a handcoloured print in the copies of Astronomiae Instauratae Mechanica that Tycho gave to noblemen of Europe. See that Tycho's right eye is bigger than his right eye after many observations. Wandesburg 1598." For further details, see http://www.nada.kth.se/~fred/tycho/index.html

Another Nose

Brahe later received at least one replacement nose for his first replacement nose. We know this because when his body was exhumed, a light greenish coloration on his front cranium was interpreted to be remains of a metal mixture that included copper. The original replacement nose –the nose that everybody had been looking forward to seeing – was, however, gone. The thin metal had corroded, and the coffin made of zinc may have speeded the corrosion process.

Another Accident

Another accident ended even worse for Brahe. One day, he sent his pet moose over to the castle of Landskrona, a city close to Hven, to entertain a nobleman there. The moose was less interested in dinner conversation than in the castle interiors, and gave itself a tour of the building. Since the animal was completely drunk by that time – people had given the moose too much beer to drink – it fell down the stairs, and broke one leg. Shortly after, it died from the wound. (This incident was reported by Gassendi in 1654; readers who take the trouble to look up its history will be entertained or aghast, depending on their feelings about animal rights, about the morality of anyone or anything drinking alcoholic beverages, and about the ergonomic deficiencies of the period's architectural designs.)

A Side Note on Duels

By the way, duels by rapier or pistol did not, er, die out in Germany until the nineteenth century, despite being severely forbidden by law. Even the German Head of the State Bismarck, who took part in many duels as a student, in all seriousness asked the famous professor of medicine Rudolf Virchow for a duel in 1865! The two were political rivals, and Bismarck felt that Virchow had disrespected him by accusing Bismarck of not having read a report relating to the abolition of the German navy. The men did not duel, and so were able to go through life with noses intact.

Acknowledgements

A big thank you to Peter Schaible, who translated the original paper describing the exhumation ("Tycho Brahe," Casopis Spolecnosti Pratel Starozitnosti ceskych v Praze, J. Herain and J. Matiegka, vol. 9, 1901, pp. 105-30) from Czech into German. A general source is Tycho Brahe, the Man and His Work (original in Latin) by Pierre Gassendi, 1654. This book was translated into Swedish, and commentary added, by Wilhelm Norlind in 1951.

Figure 3: Brahe's cranium 300 years after his death.

Heliocentric Solar System

Understanding the true motions of planets

Danish astronomer *Tycho Brahe* was the best observer of stellar and planetary motions before the onset of telescopes

He was also a *party animal* who

- ✓ *lost his nose* in a sword duel as a young man
- ✓ *drank heavily*

Heliocentric Solar System

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Danish astronomer *Tycho Brahe* was the best observer of stellar and planetary motions before the onset of telescopes

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- ✓ *lost his nose* in a sword duel as a young man
- ✓ *drank heavily*

and

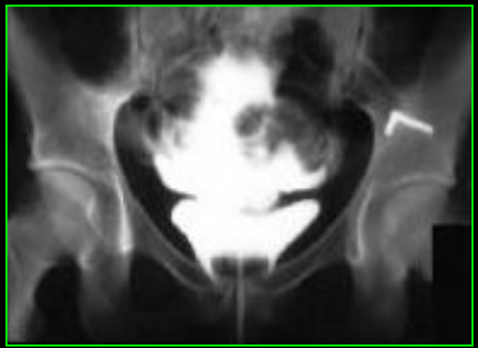
- ✓ may have died of a *burst bladder*

Heliocentric Solar System

Understanding the true motions of bladders

A friend of Brahe delivered the funeral oration and described his last days:

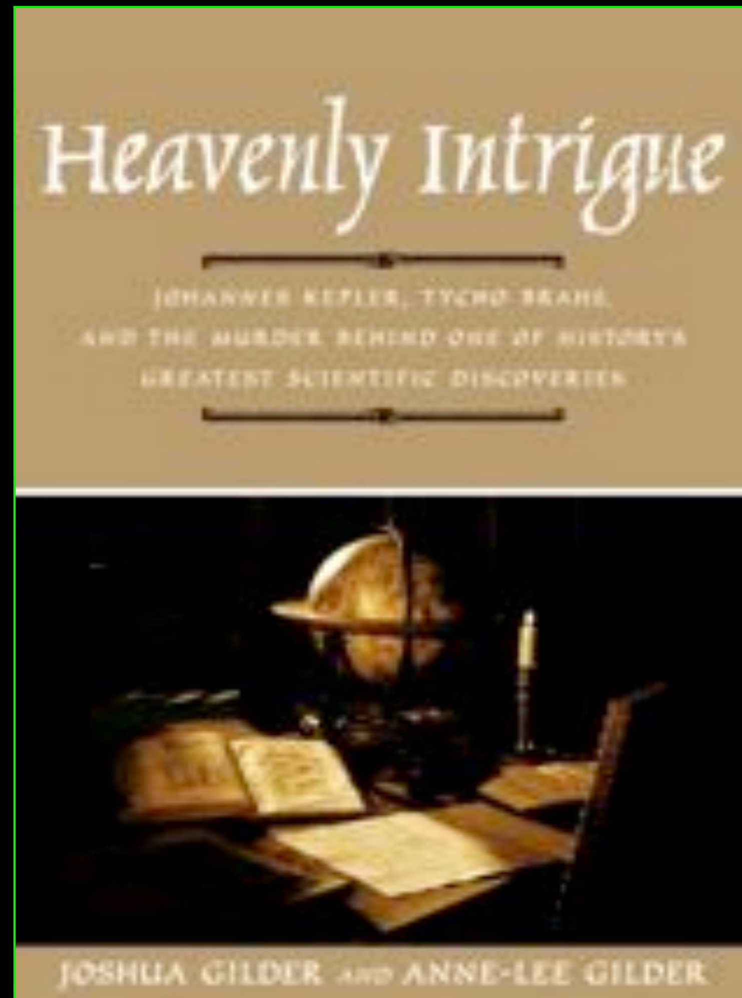
"The day on which he fell sick was October 13…
For at the dinner of an illustrious man, dining with others as a guest, Tycho suppressed his urine, which, having been increased by the drawn-out assembly, so distended his bladder that, as if displaced, afterward it did not obey any more the wanting to cleanse."



Kepler's Three Laws

Foul play?

Journalists and authors
Joshua and Anne-Lee Gilder
make a case in their book
"*Heavenly Intrigue*" (2004)
that Tycho Brahe's assistant
Kepler *poisoned* Tycho
to get access to his data faster!




TYCHO BRAHE
BRIS OBIIT ILLVSTRIS & GENEROSVS DNVS TYCHO BRAHE

follicles of Tycho’s beard

Kepler’s Three Laws

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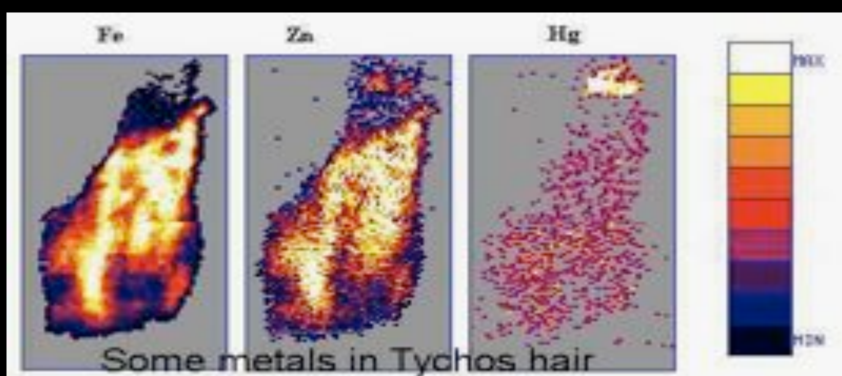
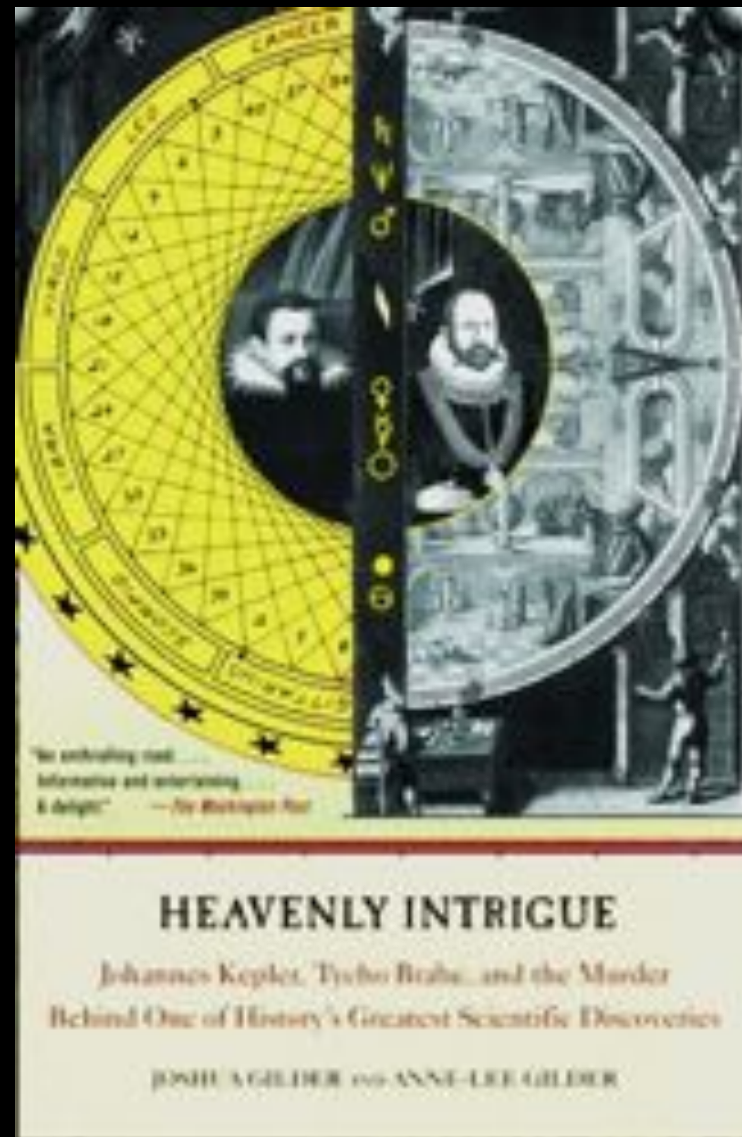
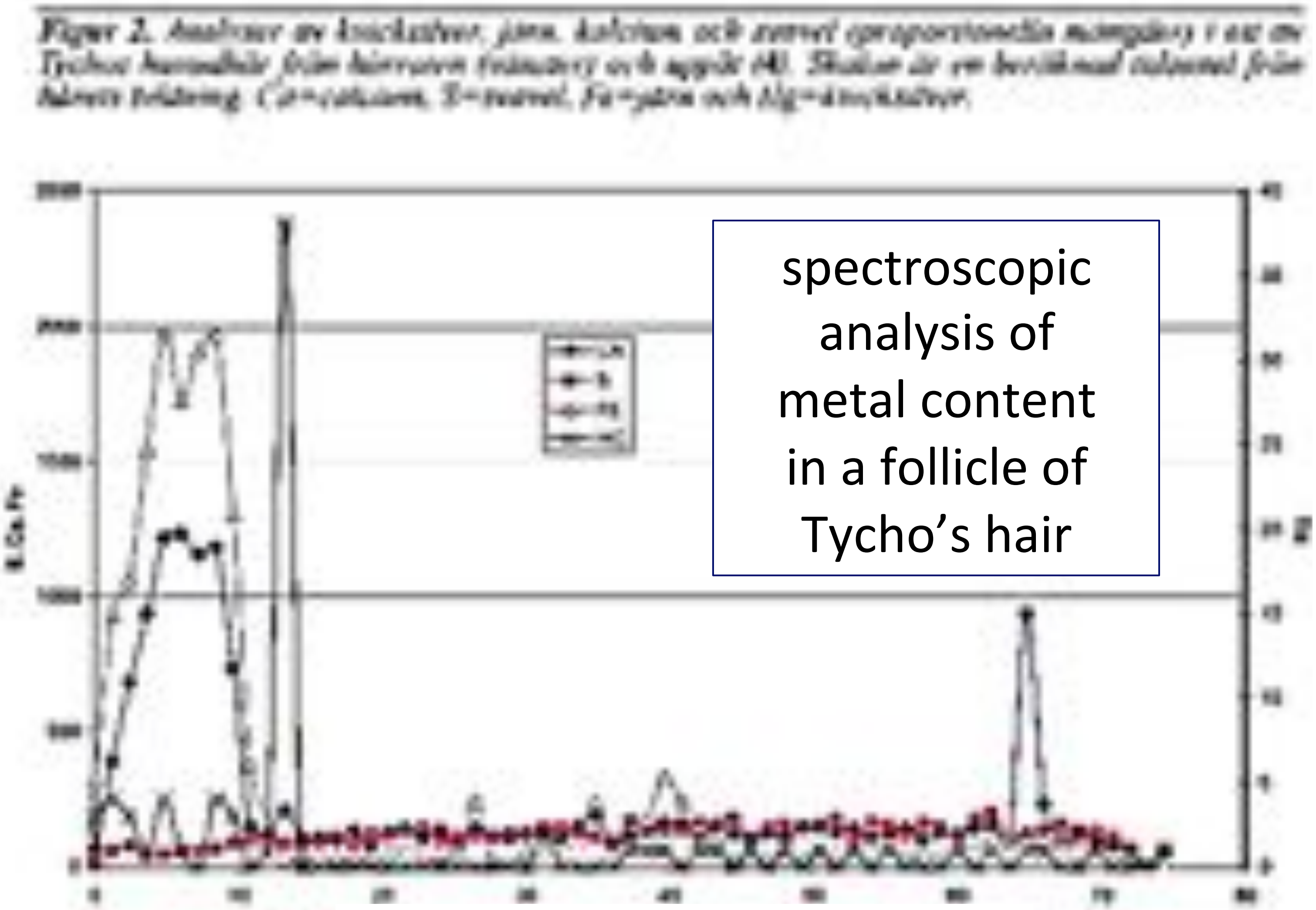


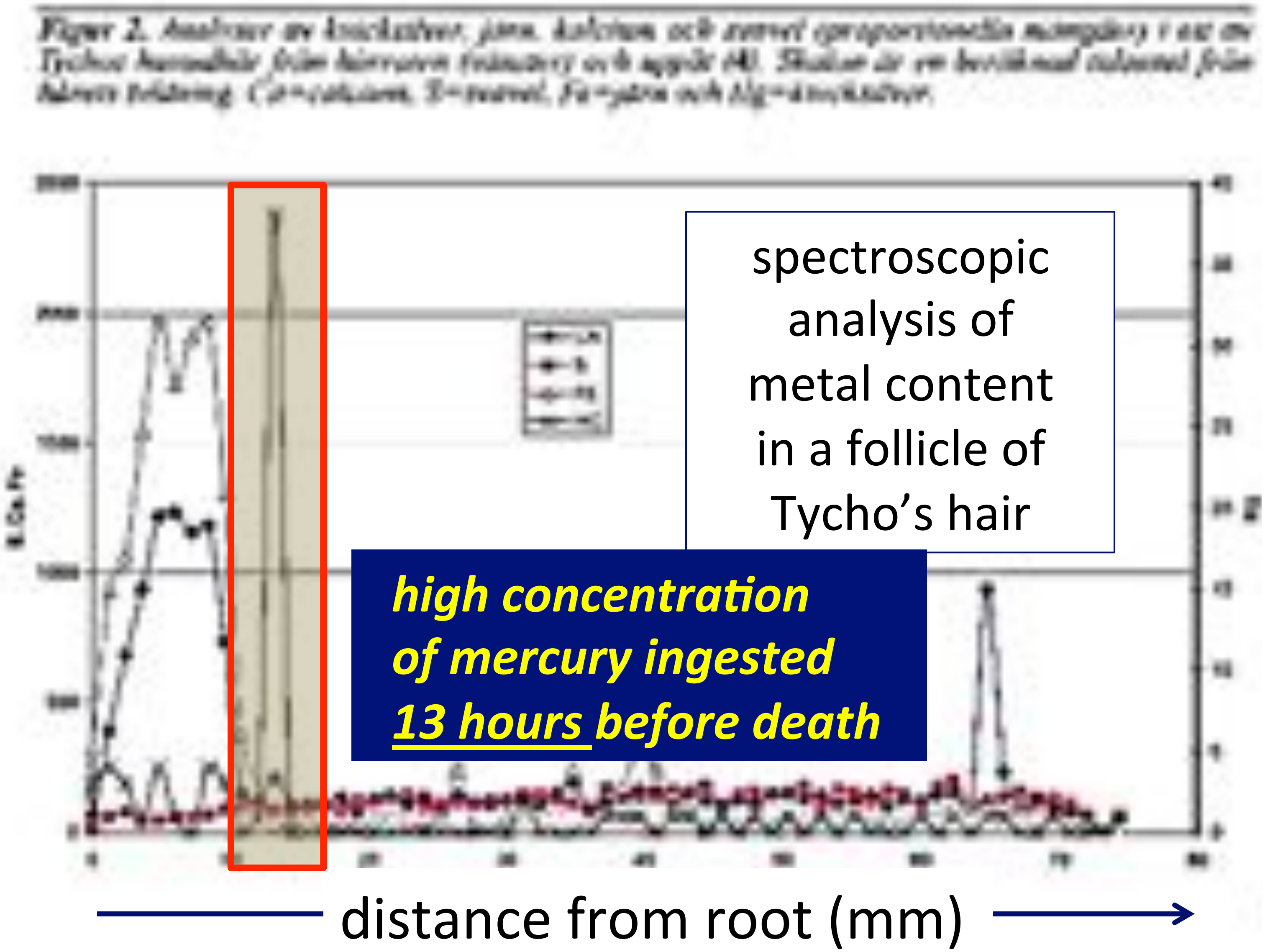
analysis of a hair follicle from Tycho’s tomb





distance from root (mm)

Jan Pallon (Lunds University, Denmark)



Jan Pallon (Lunds University, Denmark)

The suspect

"He was a quiet man … "

Johannes Kepler, a German mathematician hired as Tycho's assistant, took two decades to correctly interpret Tycho's measurements of the positions of the planet Mars in the sky

Kepler's Three Laws

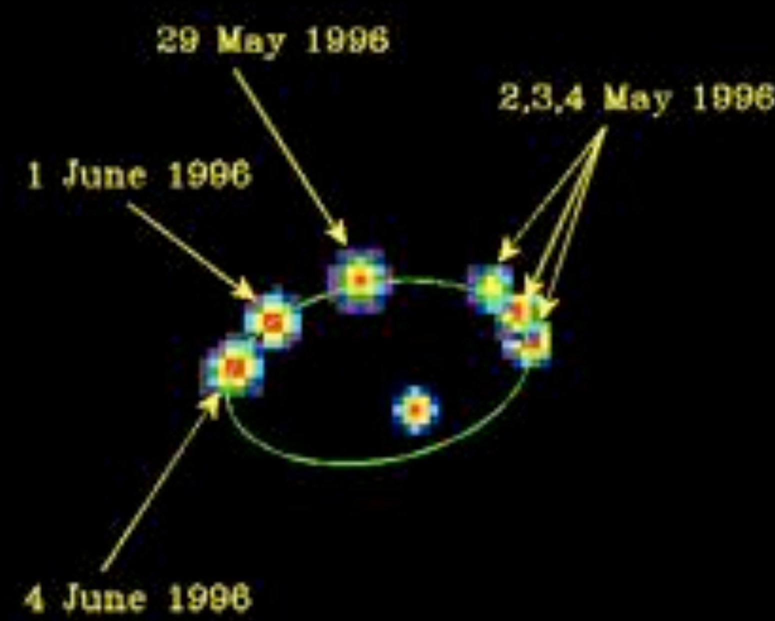
Principles of planetary motion

Johannes Kepler, a German mathematician hired as Tycho's assistant, took two decades to correctly interpret Tycho's measurements of the positions of the planet Mars in the sky

Kepler's Three Laws

Principles of orbital motion

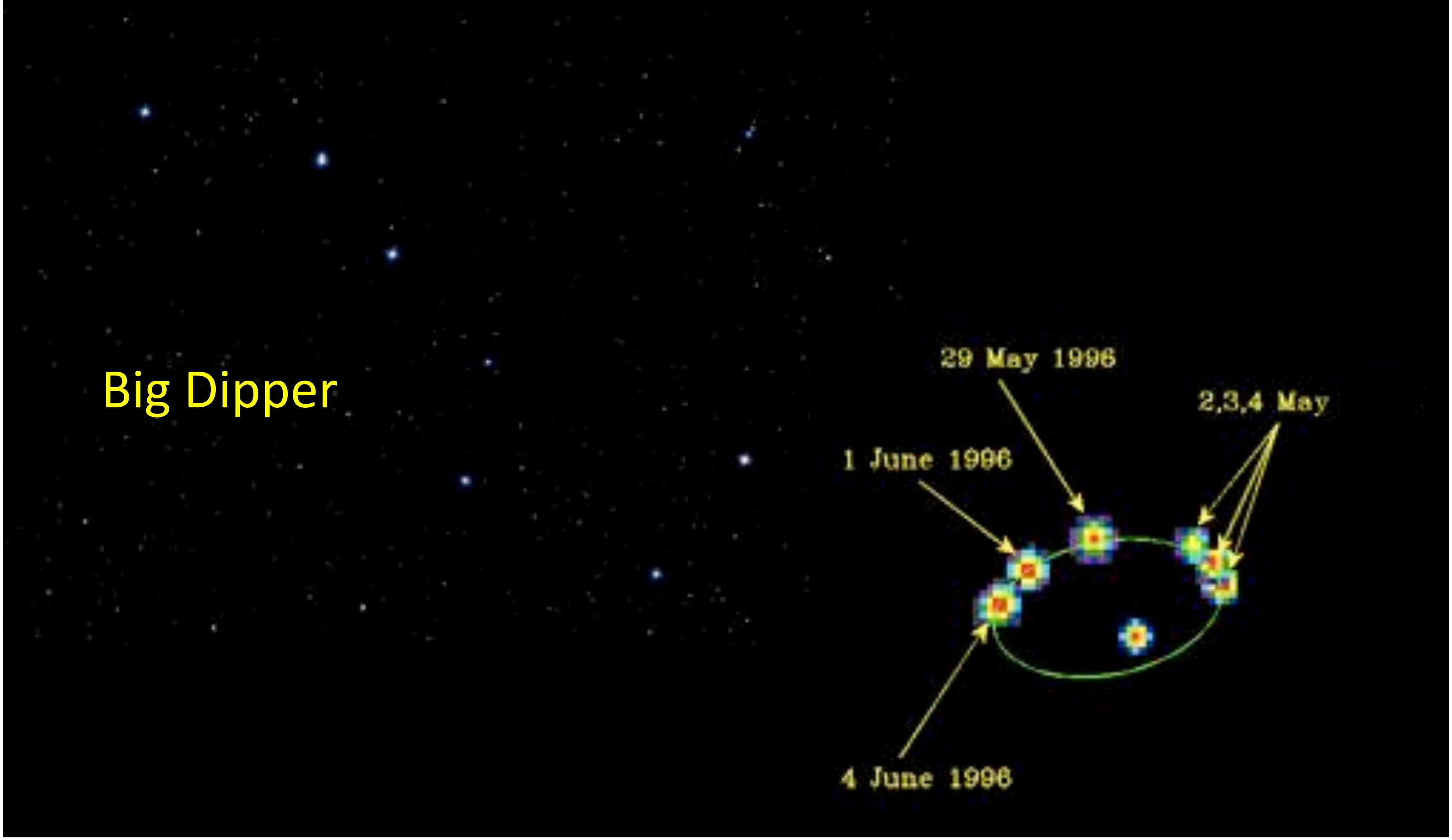
Johannes Kepler, a German mathematician hired as Tycho's assistant, took two decades to correctly interpret Tycho's measurements of the positions of the planet Mars in the sky



His *three laws of planetary motion* are still used today, and also apply to the orbits of moons and artificial satellites around planets, *binary star orbits*, and *orbits of galaxies in clusters*

Kepler's Three Laws

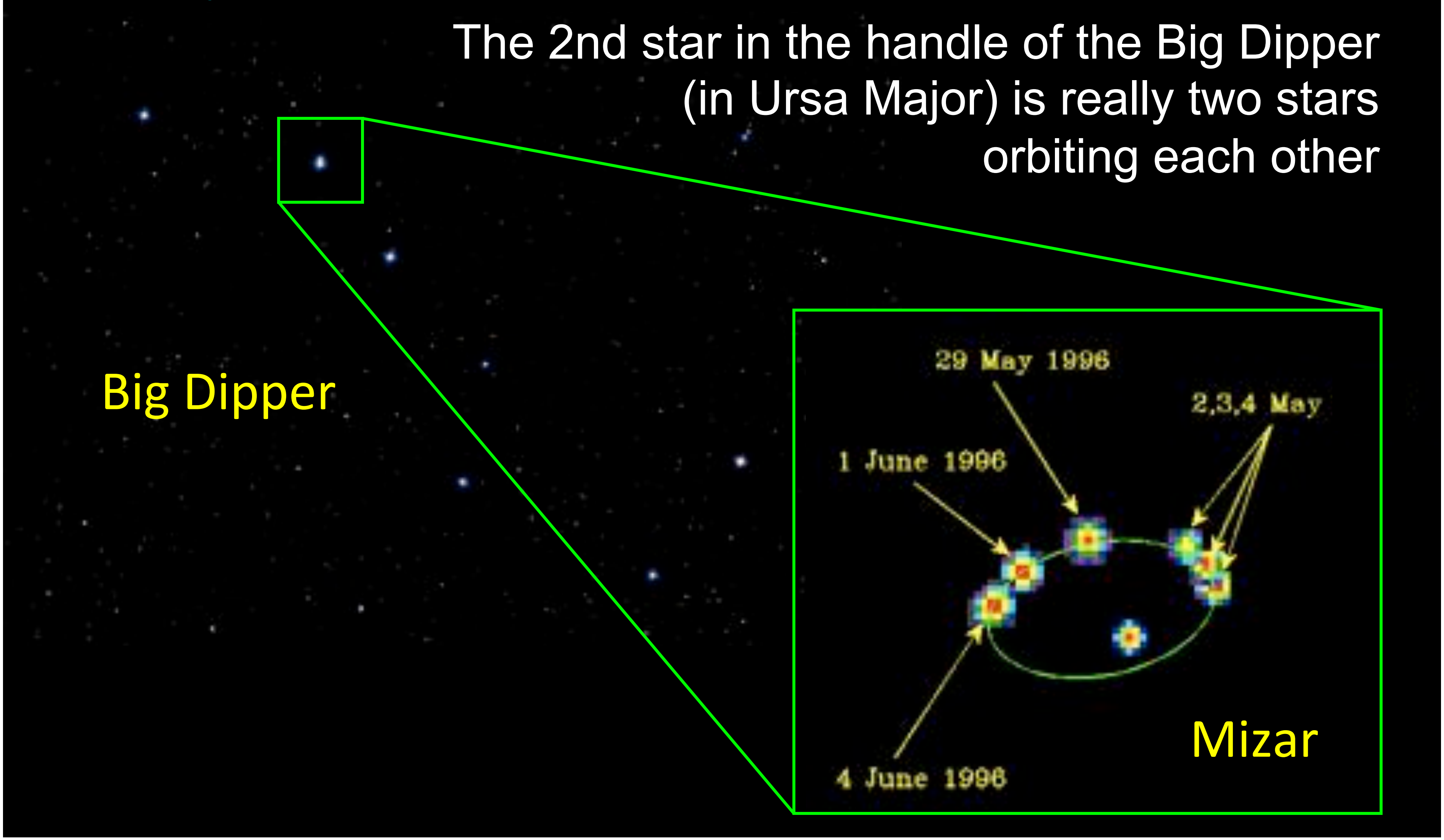
Binary stars



Kepler's Three Laws

Binary stars

The 2nd star in the handle of the Big Dipper (in Ursa Major) is really two stars orbiting each other



A question of morality?

Q. What would *you* do to possess the most exquisite scientific data on Earth?

A question of morality?

Q. What would *you* do
to possess the most
exquisite scientific data
on Earth ?

A? Go Kepler on your supervisor!

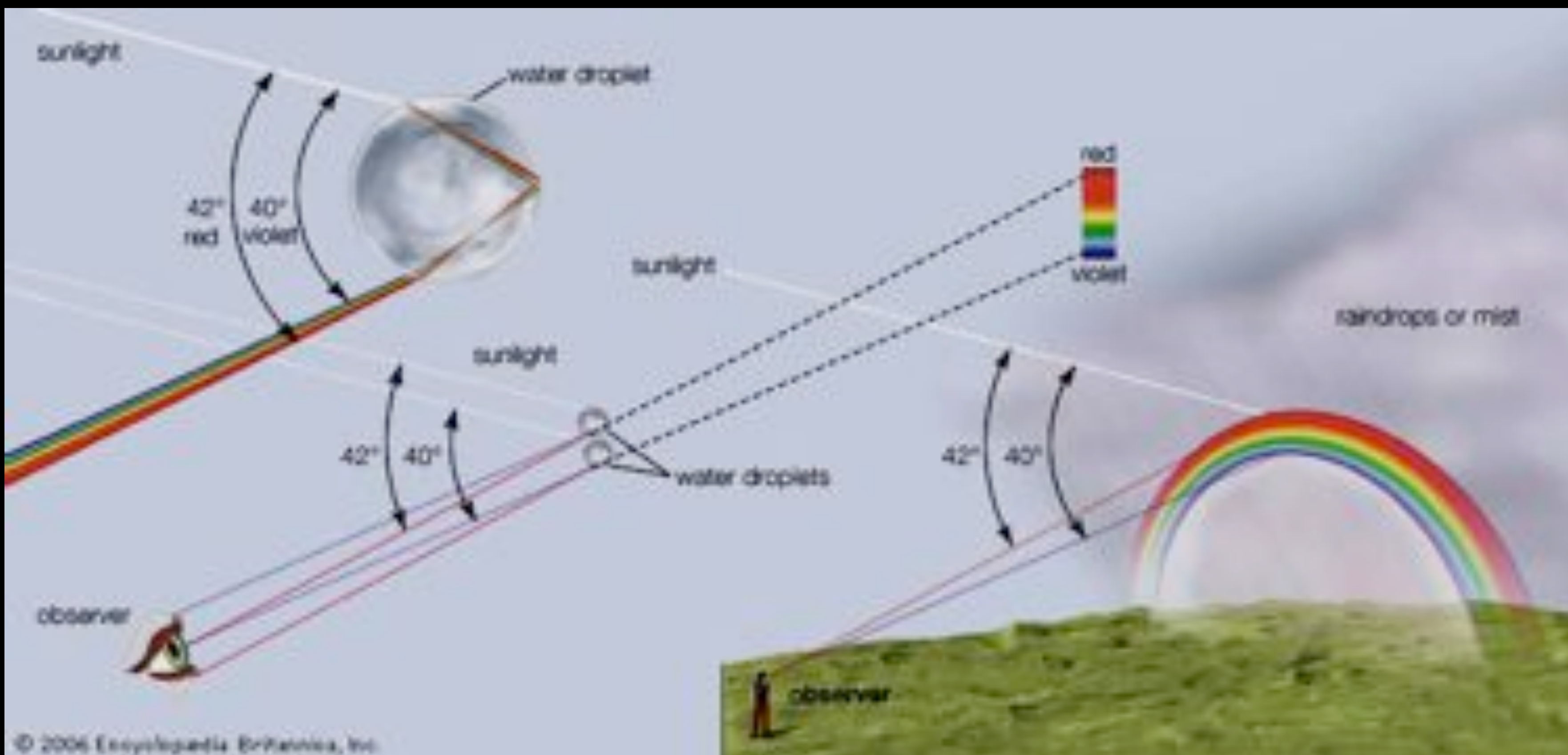
One last question

Q. What are the stars made of?


Spectroscopy
How is a rainbow formed?

Spectroscopy

Water droplets suspended in the air during or after a rain shower refract and partially reflect sunlight. The angle of refraction depends on the wavelength of the light, so the raindrops spread the white light of the sun into a spectrum



Spectroscopy

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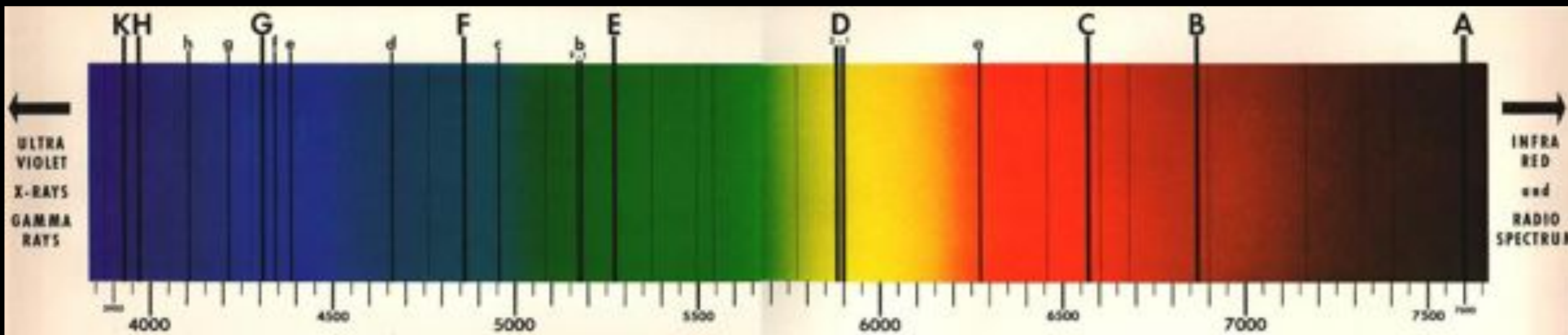
Spectroscopy

What's hidden in a rainbow?



A high-resolution look at the visible spectrum of sunlight reveals dark lines in addition to the bright background with the familiar colours of the rainbow

Spectroscopy

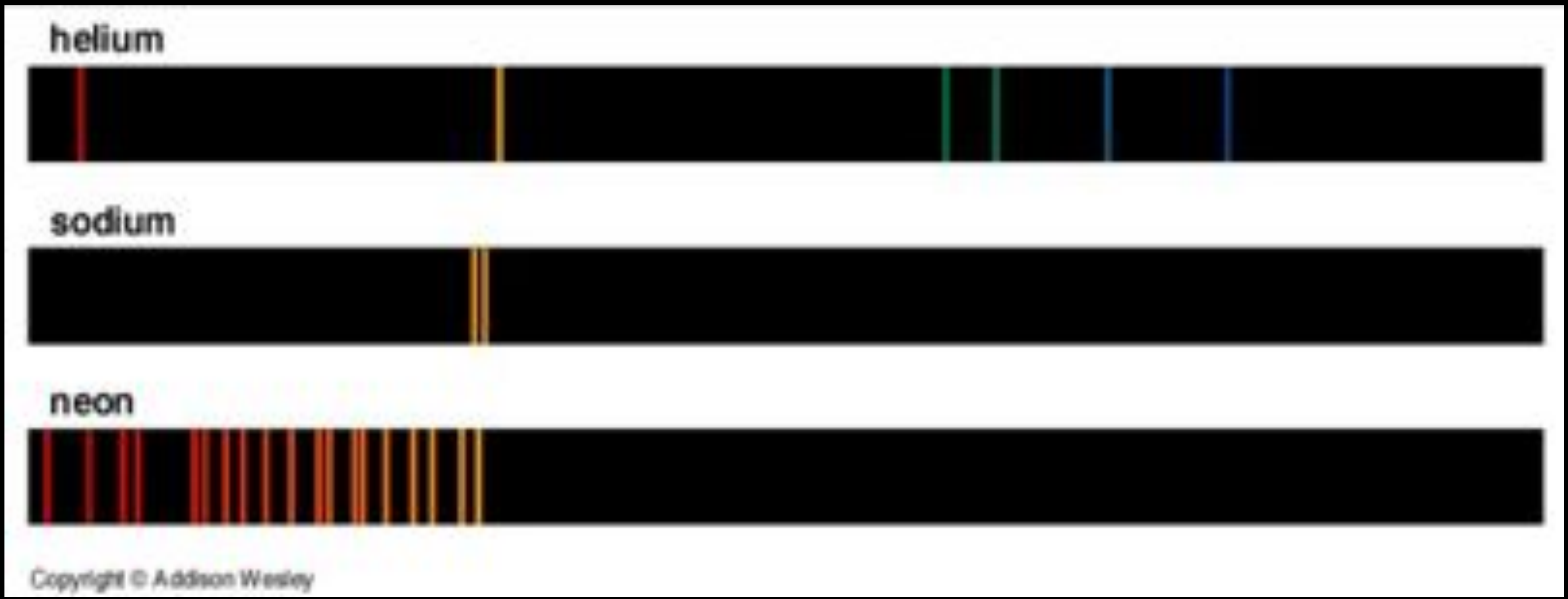
What's hidden in a rainbow?

These dark lines were observed in the solar spectrum by optician *Joseph von Fraunhofer* in 1813, so they became known as *Fraunhofer lines*

Spectroscopy

Spectral classification

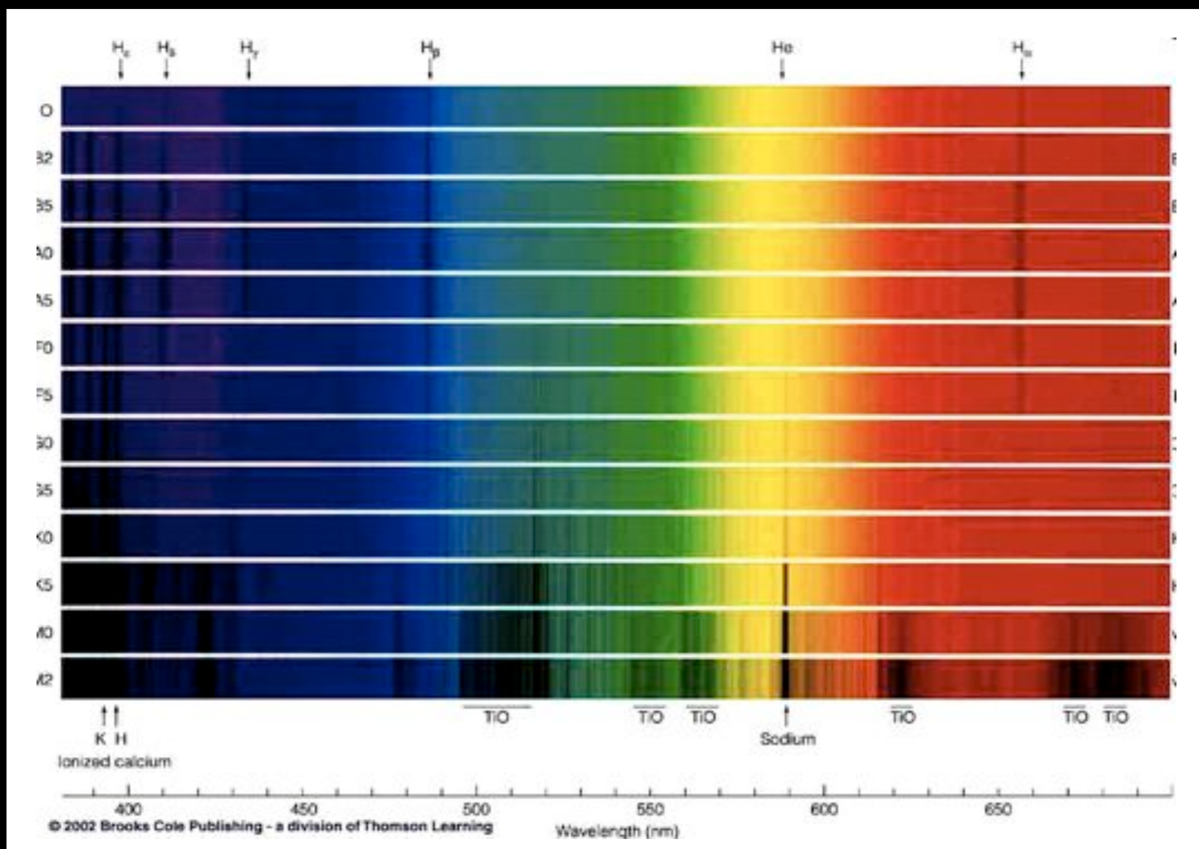
Each atom (ion) has its own pattern of spectral lines which we can use to recognise the elements in a gas



Spectroscopy

Spectral classification

The spectra of stars contain
the absorption line patterns of atom, ions and molecules

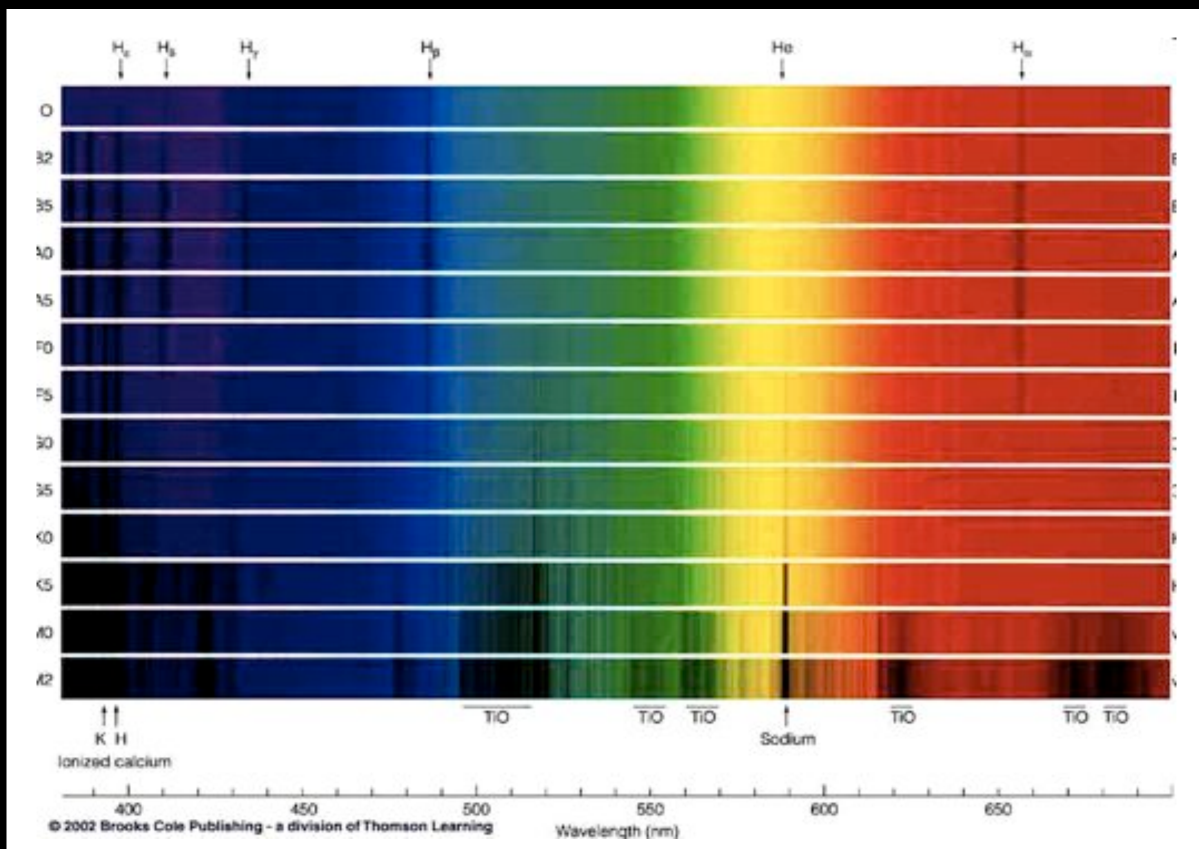


Spectroscopy

Spectral classification

The spectra of stars contain
the absorption line patterns of atom, ions and molecules

temperature T



The strengths of those lines depends sensitively on the surface temperature of the star

Spectroscopy

Spectral classification

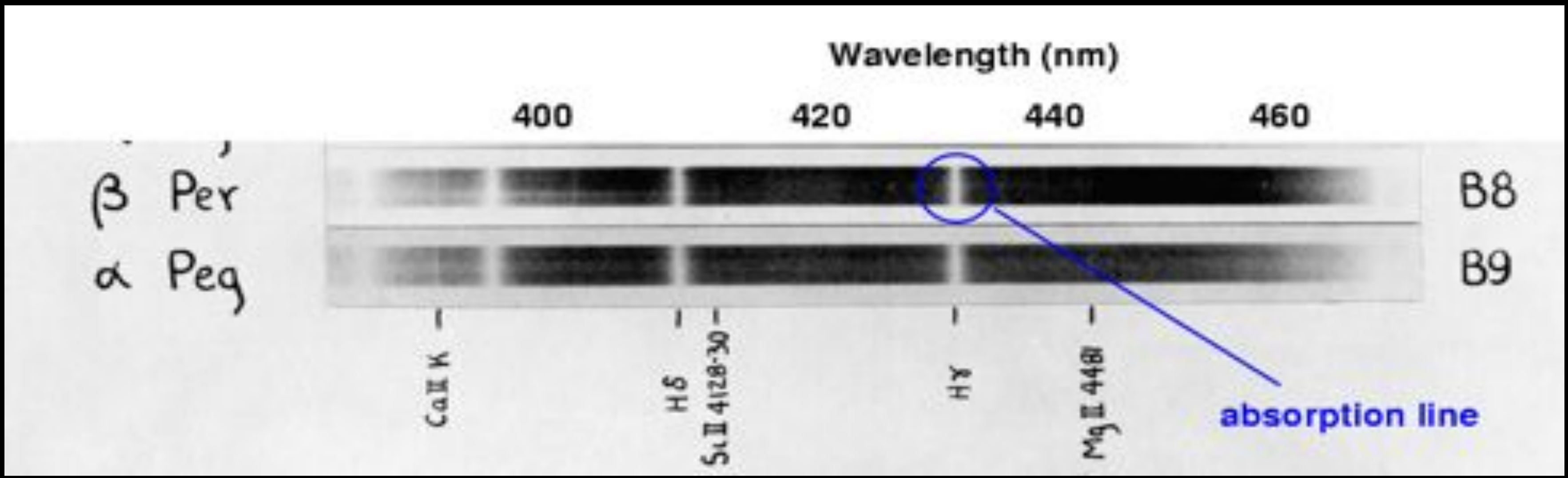
Originally, astronomers sorted stellar spectra in order of the strength of the hydrogen Balmer lines

strongest Balmer lines

alphabetically from A to O

weakest Balmer lines

photographic spectra
from the old Harvard Observatory
negative – so dark absorption lines show up as bright features



Spectroscopy

Spectral classification

During World War I
Edward Charles Pickering
Director of the Harvard
College Observatory
hired women to serve as
"calculators" to help with his
new survey of the Milky Way

Most of these women
had studied astronomy
but were not allowed
by law to work as scientists

Spectroscopy

Spectral classification

During World War I
Edward Charles Pickering
Director of the Harvard College Observatory
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Most of these women had studied astronomy but were not allowed by law to work as scientists

His scoffing (male) colleagues dubbed this team of women "*Pickering's Harem*"

Spectroscopy

Spectral classification

These women were patient and meticulous classifiers of the photographic spectra they received from Pickering

Spectroscopy

Spectral classification

These women were patient and meticulous classifiers of the photographic spectra they received from Pickering

Among them was a particularly talented and insightful woman: *Annie Jump Cannon* (1863 – 1941)

Spectroscopy

Spectral classification

Cannon personally classified over a quarter of a million individual stellar spectra – tiny faint patterns on glass photographic plates

Spectroscopy

Spectral classification

She loved what she did so much that this was the Christmas card she sent to family and friend in 1915, describing stellar spectra

THE STORY OF STAR LIGHT.

Since 1882, with increasing skill, astronomers have been able to photograph star light in such a manner that the marvelous wireless message from the distant body may be deciphered. The light from the star is allowed to fall through a prism placed in the telescope and, thus magnified, is split up into a band showing its component colors, the red rays going to one end, and the violet to the other. This is the spectrum of the star. The photograph does not show the colors, but, what is more important, it does show the presence of fine dark lines, few in some spectra and numerous in others. These wonderful dark lines have become a veritable happy hunting ground for the modern astronomer. By comparing them with lines given by glowing substances in his own laboratory, he can determine that the same elements familiar to us on the earth also exist in the outermost star. By measuring the positions of these mysterious lines he can discover whether a star is approaching us or receding from us.

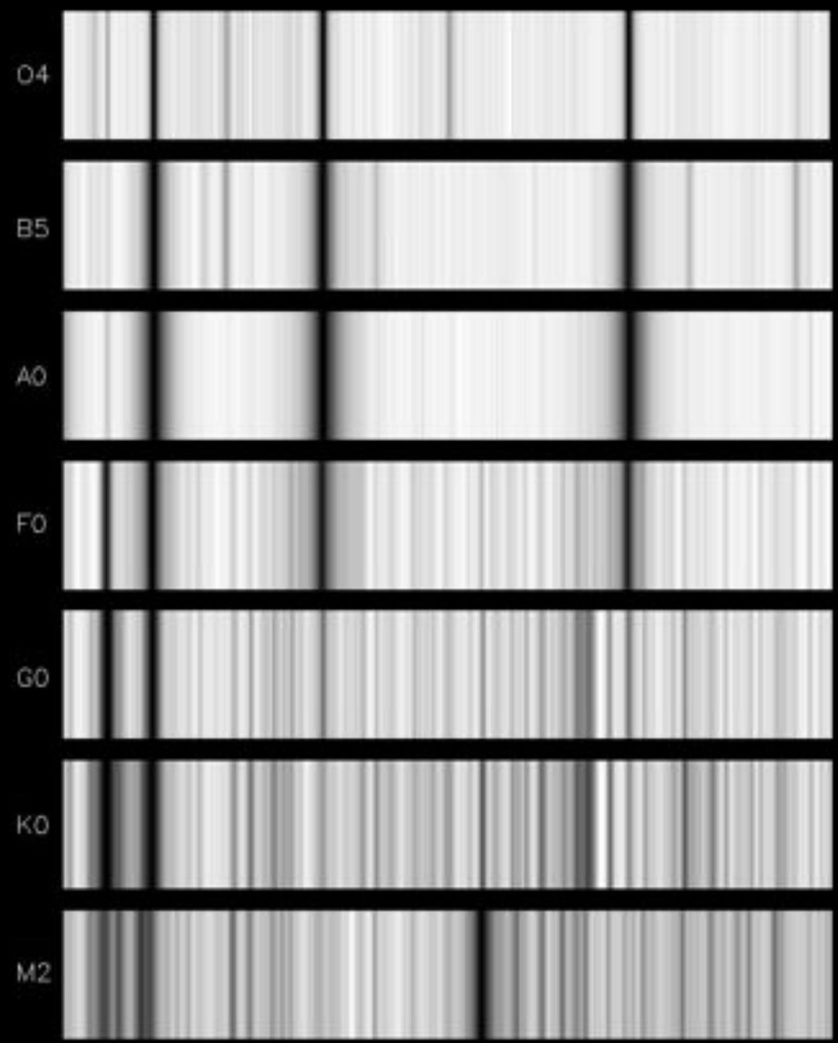
For years the whole sky from the North to the South Pole has been photographed systematically at the Harvard Observatory. We have studied in detail the lines of all the brighter stars, and have arranged the spectra in an orderly sequence, beginning with stars which appear to be "young" and very hot, going through all the stages to those which are "old" and cooler. In very recent years remarkable relations have been found to exist between the class of spectrum and other properties of the stars, such as their distances and motions. It is for this reason that astronomers engaged in various kinds of investigations wish to know the class to which the stars belong. At no other observatory is there material for this determination on such a large scale as at Harvard. It has therefore been my good fortune to make a classification of all the stars whose spectra are sufficiently clear on the Harvard photographs. The spectra of more than 200,000 stars have been studied. The results will help to unravel some of the mysteries of the great universe, visible to us, in the depths above. They will provide material for investigation of those distant suns of which we know nothing except as revealed by the rays of light, travelling for years with great velocity through space, to be made at last to tell their magical story on our photographic plates.

Annie J. Cannon

Spectroscopy

Spectral classification

Cannon realised that the strengths of hydrogen lines had a more complex behaviour and she revised the original classification scheme in a way which was later shown to depend on the temperatures of the stars inferred from their colours

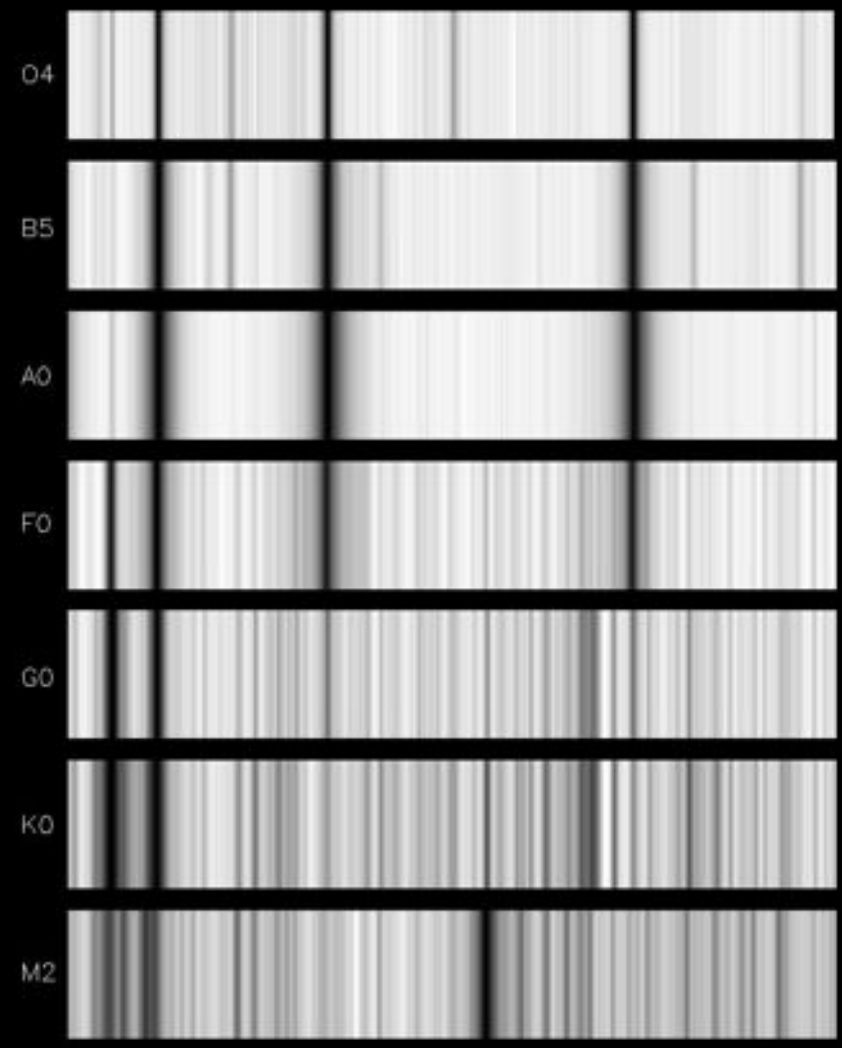


Spectroscopy

Spectral classification

Cannon realised that the strengths of hydrogen lines had a more complex behaviour and she revised the original classification scheme in a way which was later shown to depend on the temperatures of the stars inferred from their colours

She eliminated many of the arbitrary alphabetical classes and rearranged the rest in order of O to M



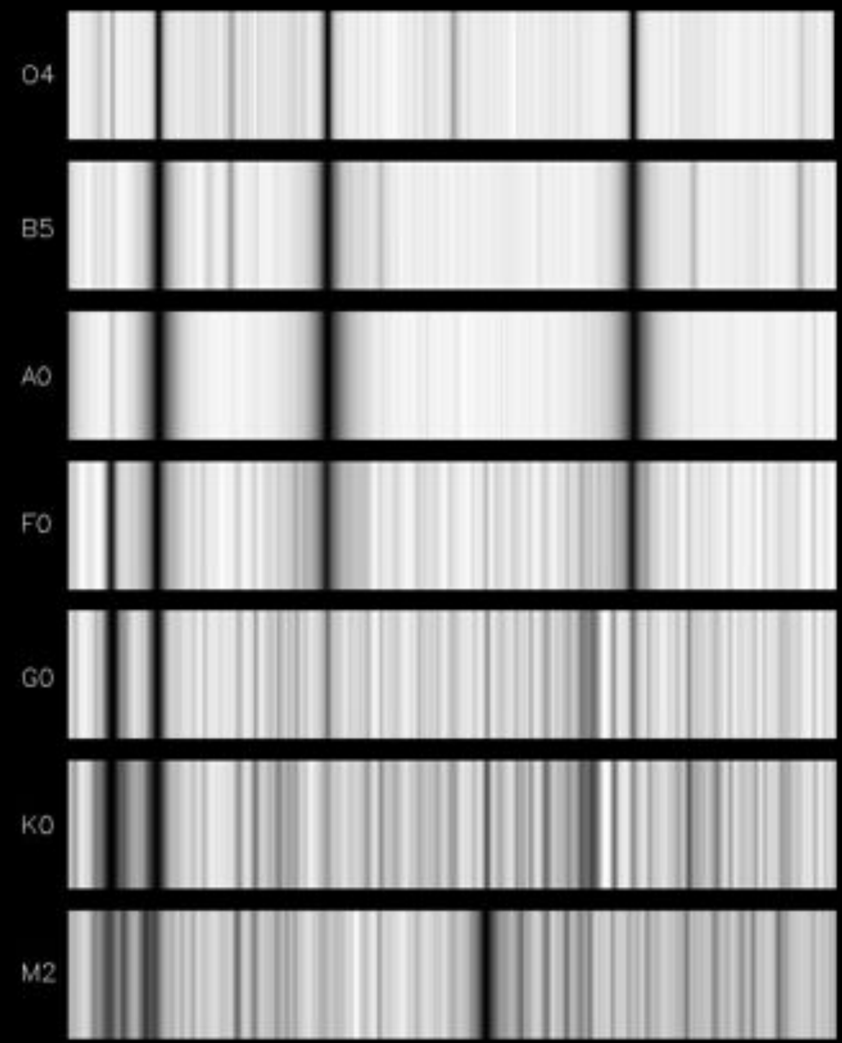
Spectroscopy

Spectral classification

ABCDEFGHIJKLMNO

became OBAFGKM

→ *cooler stars*



Spectroscopy

Spectral classification

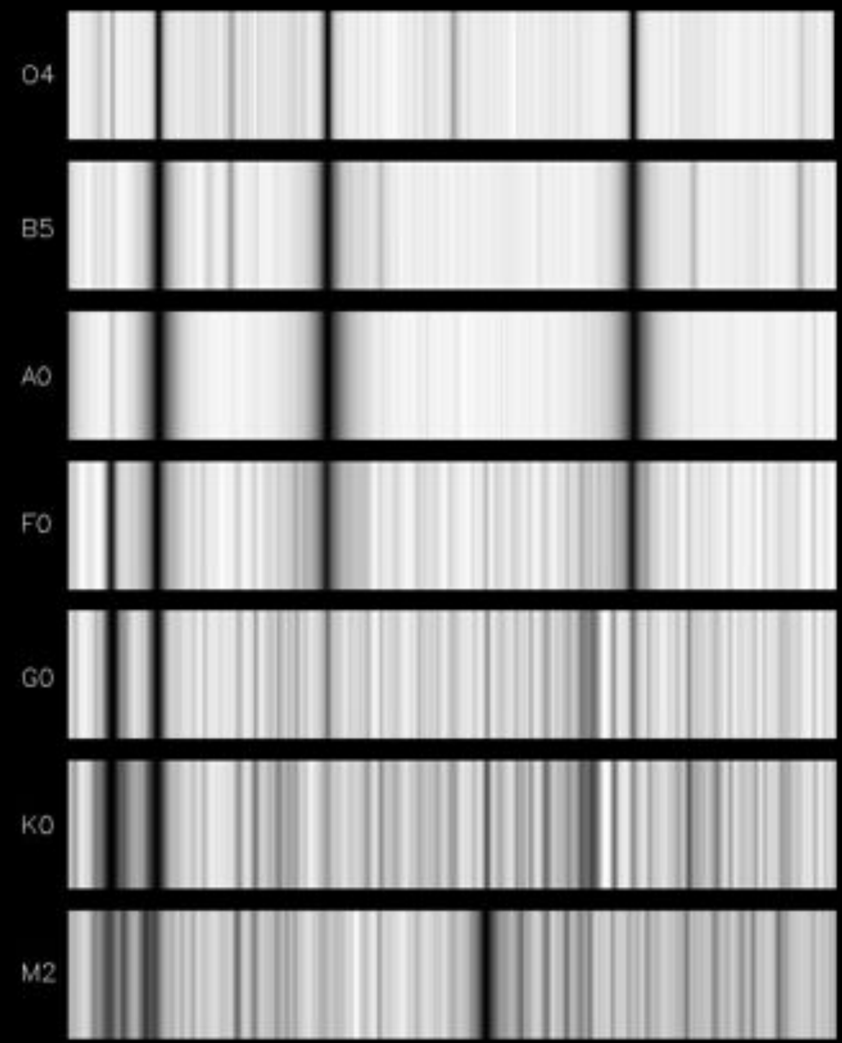
ABCDEFGHIJKLMNO

became OBAFGKM

cooler stars →

Generations of (mostly male) astronomy students memorised this spectral sequence with the following mnemonic:

"Oh, Be A Fine Girl, Kiss Me!"



Spectroscopy

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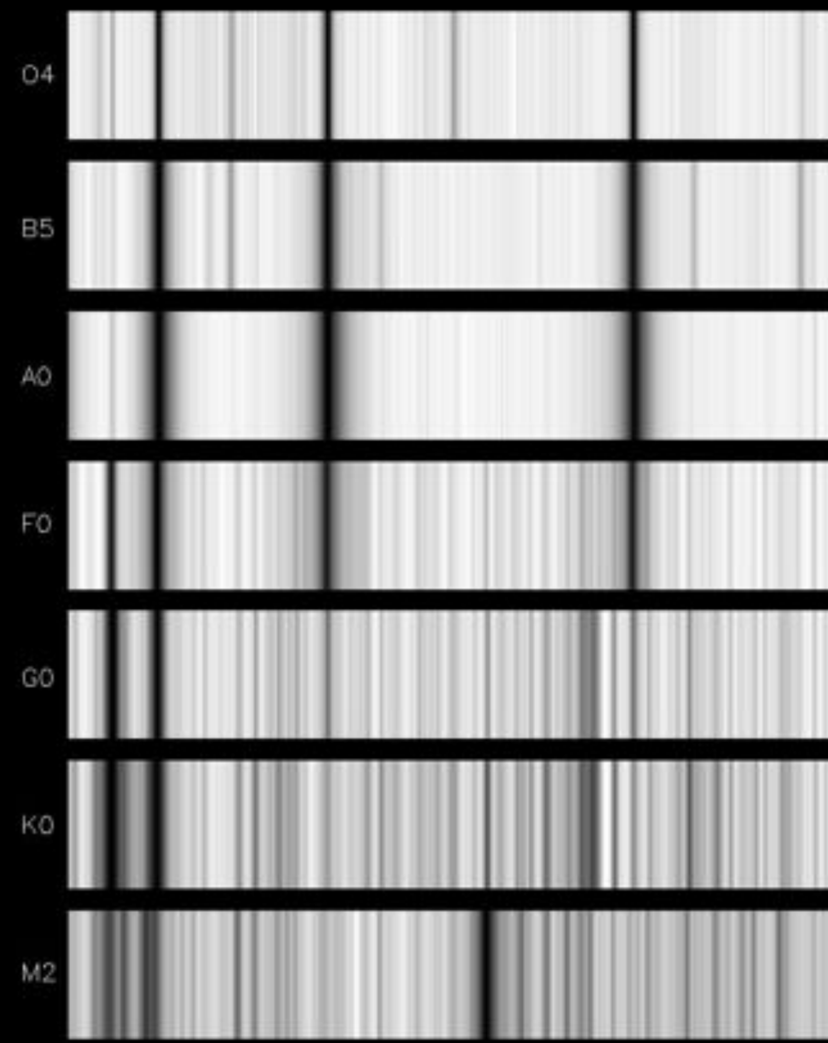
became OBAFGKM

→ *cooler stars*



Generations of (mostly male) astronomy students memorised this spectral sequence with the following mnemonic:

"Oh, Be A Fine Girl, Kiss Me!"

"Oh, Be A Fine Guy, Kiss Me!" does work for women but it's still pretty lame

Spectroscopy

Spectral jazzification

ABCDEFGHIJKLMNO
became OBAFGKM

→ *cooler stars*

A Canadian jazz singer, physicist at the University of Guelph, and astronomy enthusiast recorded a song in honour of the spectral sequence: "*Kiss Me Like That*"

Diane Nalini

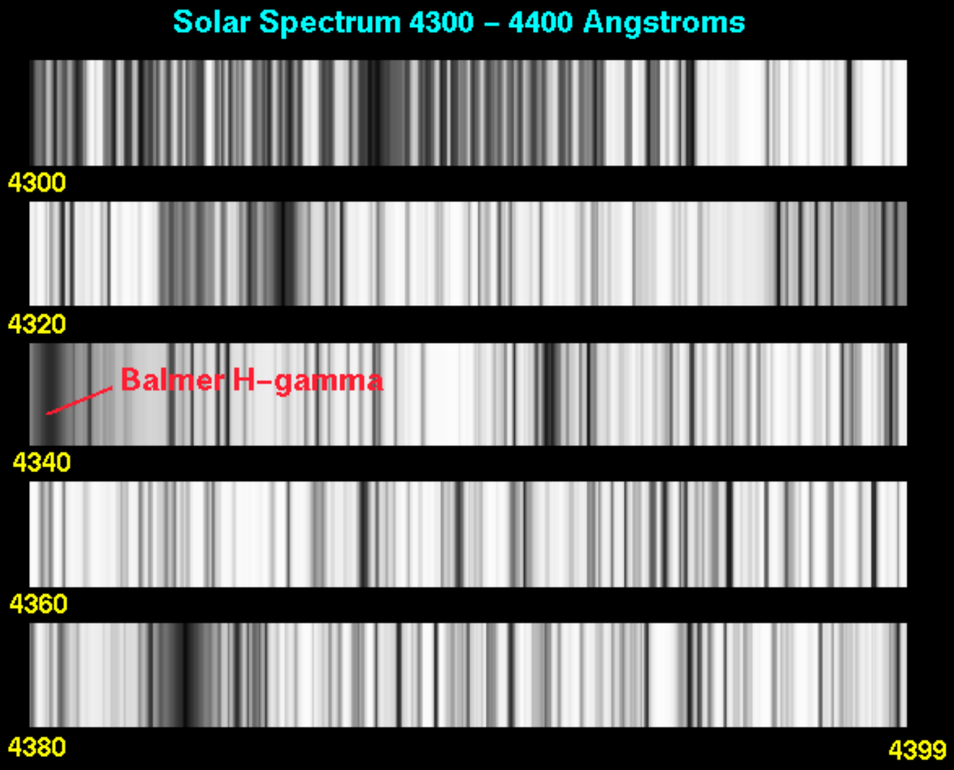
www.dianenalini.com
www.physics.uoguelph.ca/~diane

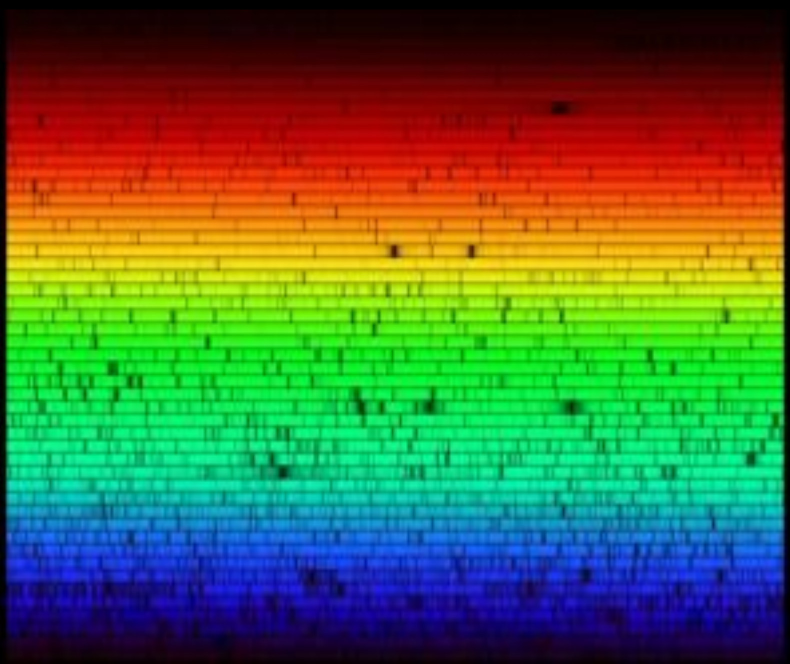
Recipe for the Sun

Composition of the Sun

What are the raw materials?

We can measure the concentrations of elements in the gas at the surface of the Sun from its absorption spectrum





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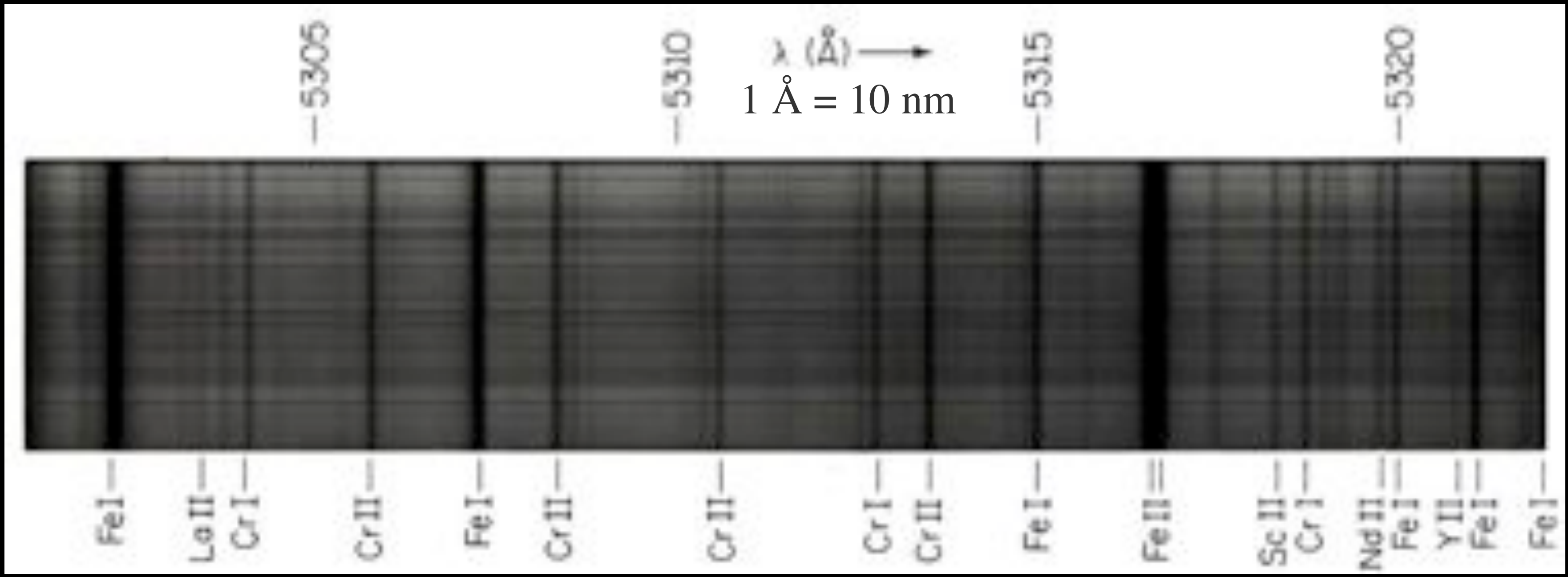

Composition of the Sun

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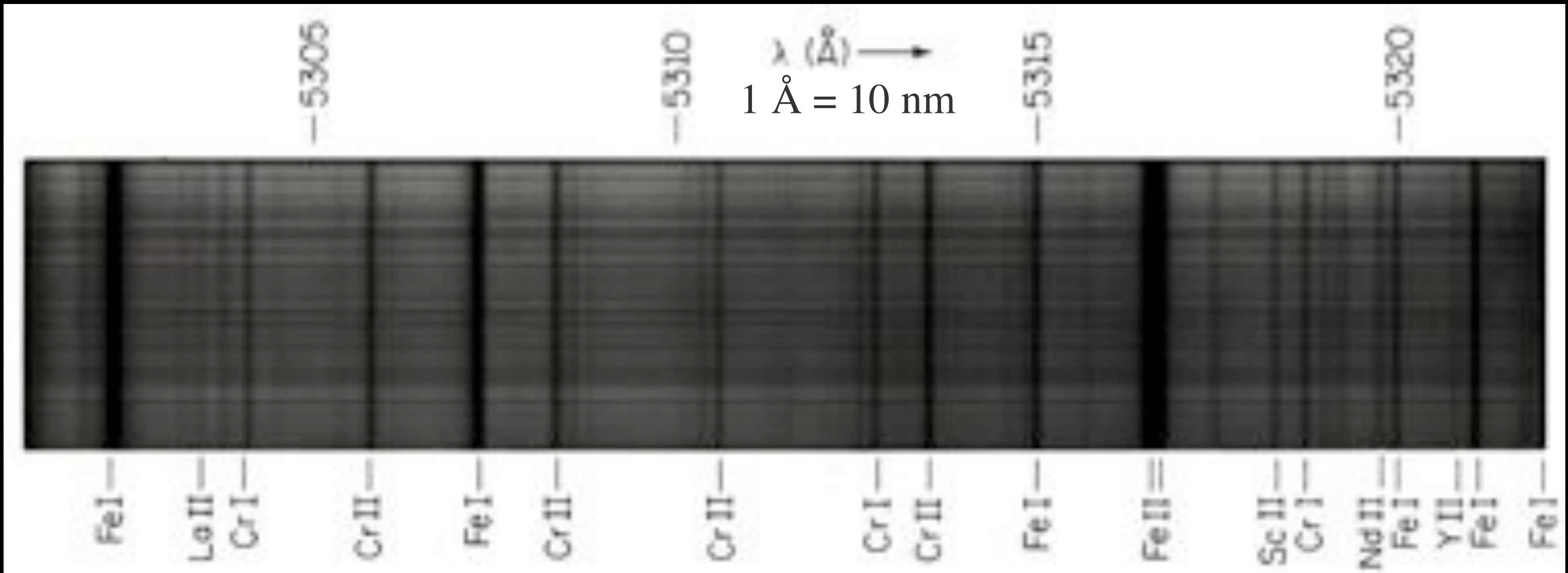
The Sun is made almost entirely of H and He



Composition of the Sun

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The Sun is made almost entirely of H and He

but astronomers didn't realise this until the late 1920s

Pioneering events in history

The world in 1927

Pioneering events in history

The world in 1927

- ✓ The first trans-Atlantic telephone call made

Canadian Prime Minister William Lyon Mackenzie King calls British Prime Minister Stanley Baldwin

Pioneering events in history

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  Canadian Prime Minister William Lyon Mackenzie King calls British Prime Minister Stanley Baldwin

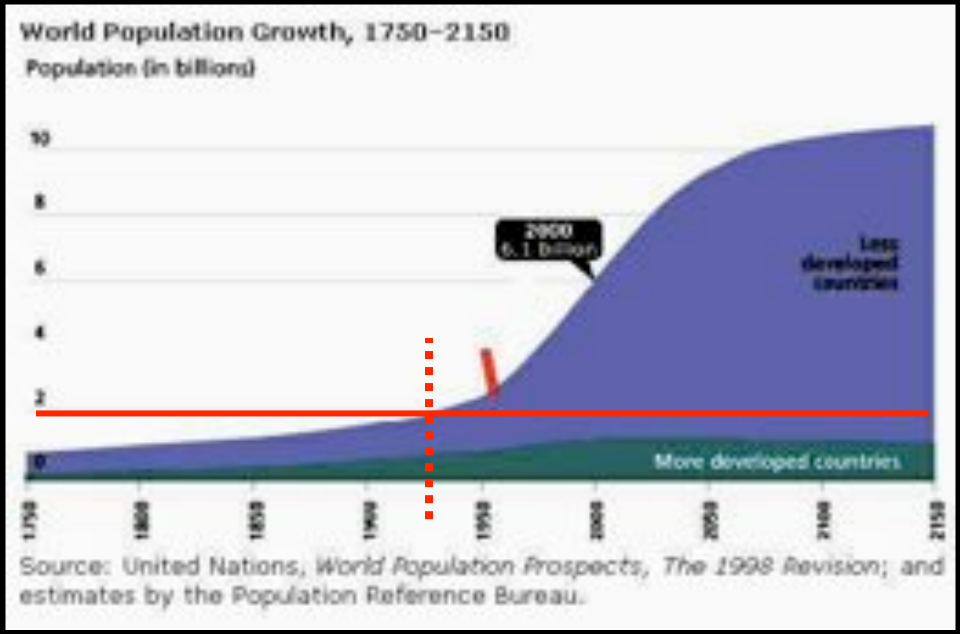
- ✓ The first solo non-stop trans-Atlantic flight by Lindbergh

Pioneering events in history

The world in 1927

- ✓ The first trans-Atlantic telephone call made

  Canadian Prime Minister William Lyon Mackenzie King calls British Prime Minister Stanley Baldwin
- ✓ The first solo non-stop trans-Atlantic flight by Lindbergh
- ✓ World population reaches 2 billion



Pioneering events in history

The world in 1927

- ✓ The first trans-Atlantic telephone call made

  Canadian Prime Minister William Lyon Mackenzie King calls British Prime Minister Stanley Baldwin
- ✓ The first solo non-stop trans-Atlantic flight by Lindbergh
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- ✓ The year *before* women were granted the equal right to vote in the UK

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- ✓ World population reaches 2 billion
- ✓ The year *before* women were granted the equal right to vote in the UK
- ✓ The year *before* sliced bread was sold for the first time
- ✓ The *Ottawa Senators* win the Stanley Cup!

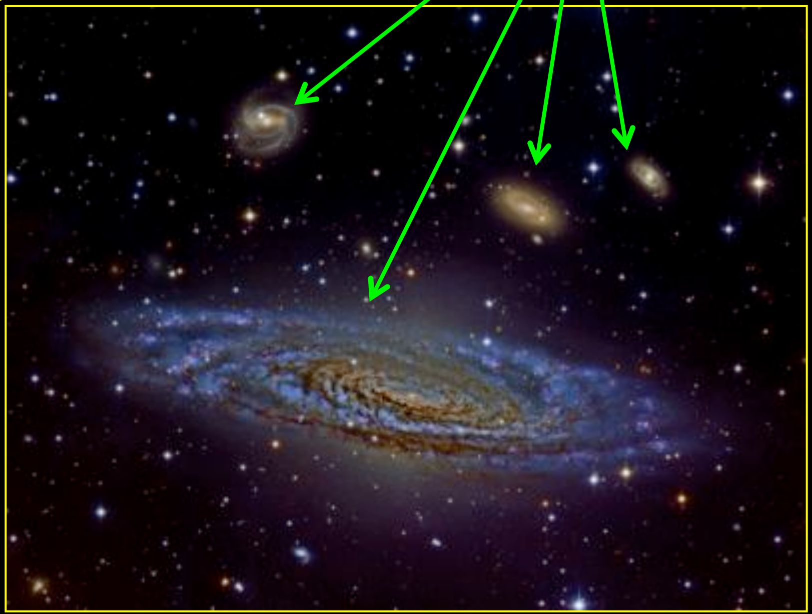
Pioneering events in history

The Universe in 1927

Astronomers at that time …

✓ … had only just come to realise that the Milky Way was *not* the entire Universe, and that there were other *galaxies*

based on Edwin Hubble's observations of a pulsating star in M31



Pioneering events in history

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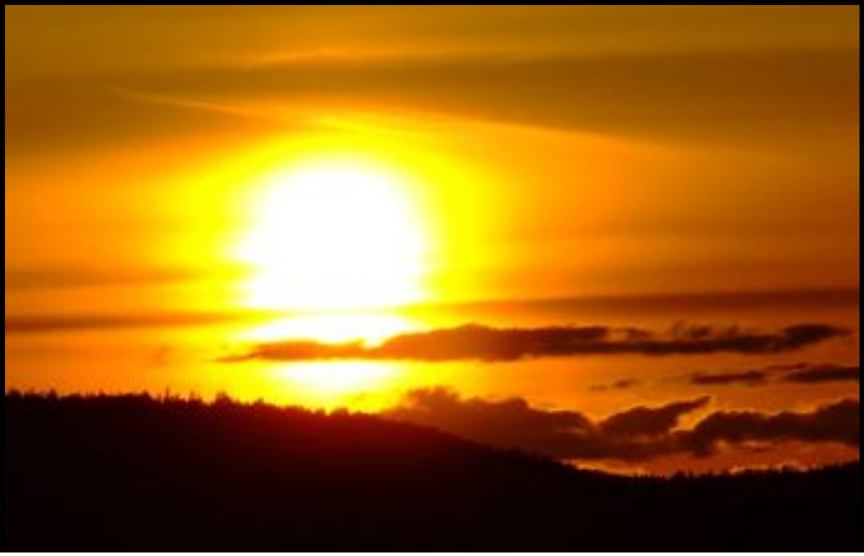
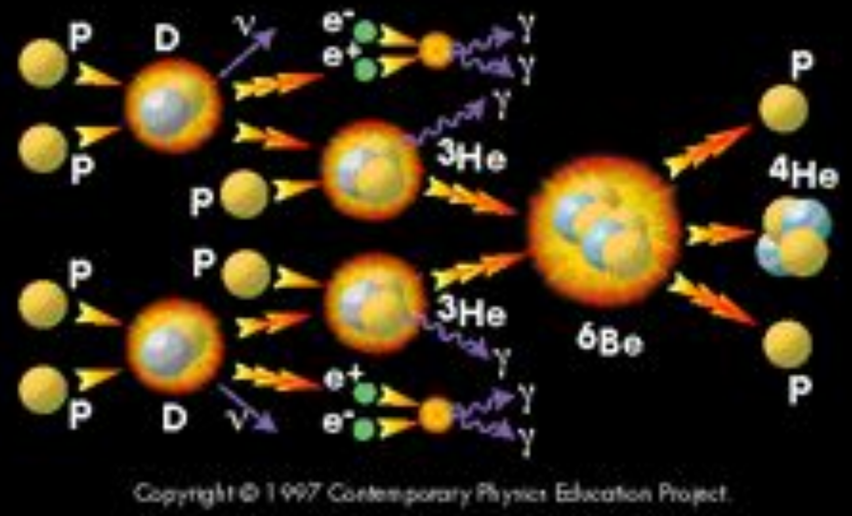
- ✓ … were about to find what causes the Sun & stars to shine
  General Relativity and nuclear physics → thermonuclear fusion





Pioneering events in history

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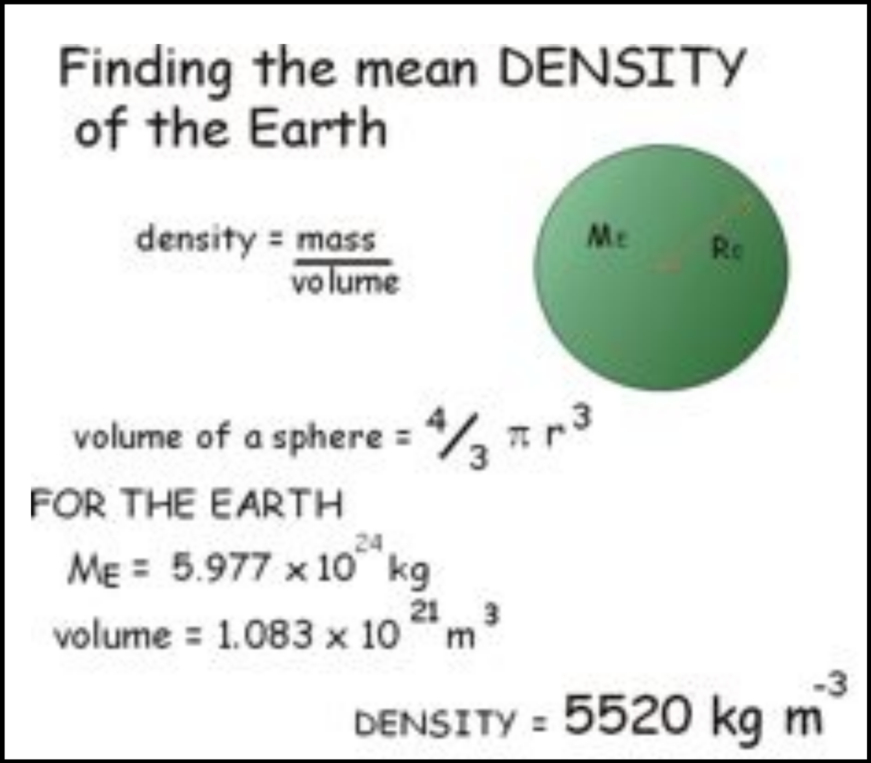
  based on Edwin Hubble's observations of a pulsating star in M31
- ✓ … were about to find what causes the Sun & stars to shine
  General Relativity and nuclear physics → thermonuclear fusion
- ✓ … believed the Sun and stars were made of iron!

This was based on reasonable observations and inferences up to that point in scientific history

Wrong for the right reasons

The iron Universe

The average density of the Earth (~5.5 g/cm^3) left no doubt that the interior of the Earth was dominated by heavy elements: iron and nickel



Wrong for the right reasons

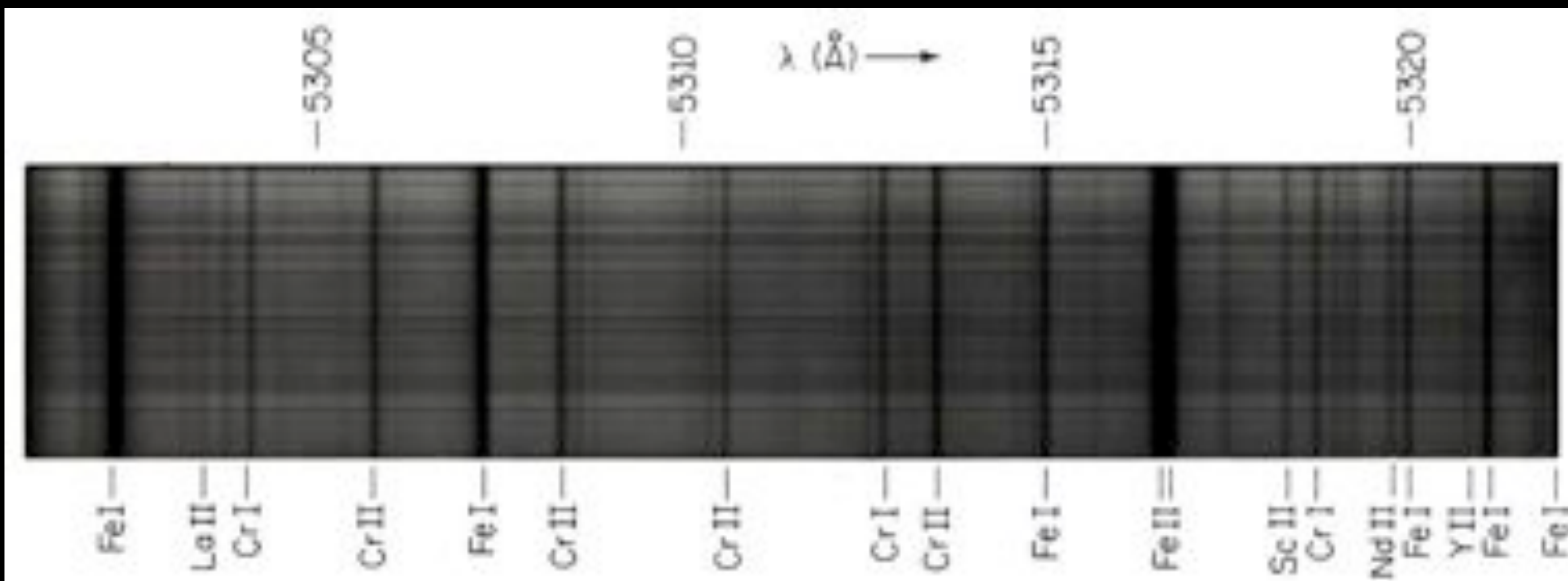
The iron Universe

Samples of the Solar System which fell to Earth – *meteorites* – were often found to be made of solid iron & nickel

Wrong for the right reasons

The iron Universe

The spectrum of the Sun was dominated by many absorption lines of iron and other chemical elements, *not* hydrogen or helium



A superhero to the rescue

The iron Universe
was not defeated by Iron Man

A superheroine to the rescue

The iron Universe
was not defeated by Iron Man
but by a clever woman
with steely resolve

Cecilia Payne-Gaposchkin
1900 – 1979

A pioneer

"Every high school student knows that Newton discovered gravity, Darwin discovered evolution, even that Einstein discovered relativity.

Jeremy Knowles
Dean of Arts & Sciences
Harvard University
February 2002

A pioneer

"Every high school student knows that Newton discovered gravity, Darwin discovered evolution, even that Einstein discovered relativity.

But when it comes to the composition of the Universe, the textbooks simply say that the most prevalent element in the Universe is hydrogen.

Jeremy Knowles
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Harvard University
February 2002

A pioneer

"Every high school student knows that Newton discovered gravity, Darwin discovered evolution, even that Einstein discovered relativity.

But when it comes to the composition of the Universe, the textbooks simply say that the most prevalent element in the Universe is hydrogen.

And no one ever wonders how we know."

Jeremy Knowles
Dean of Arts & Sciences
Harvard University
February 2002

A pioneer

A young girl looks skyward

Born in England, Cecilia was inspired to pursue astronomy when she witnessed a meteor flash across the sky one night

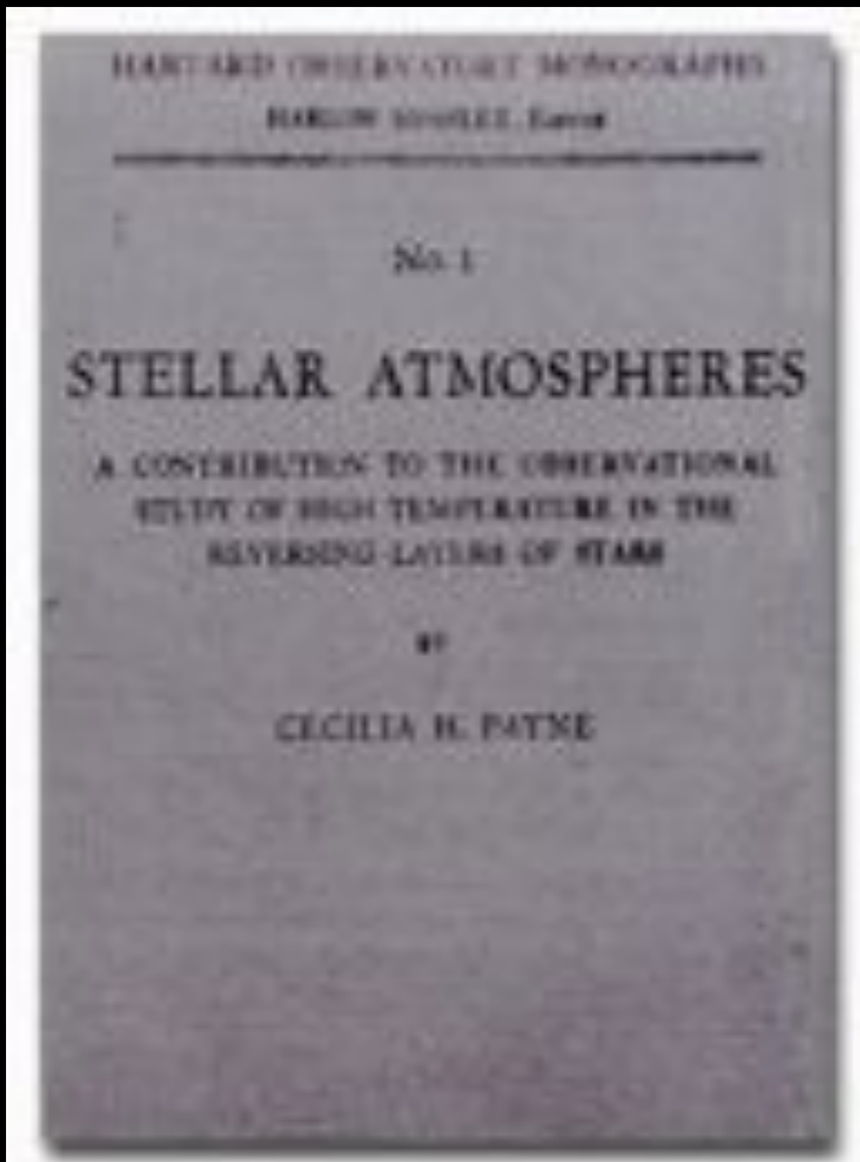
A pioneer

A rising star

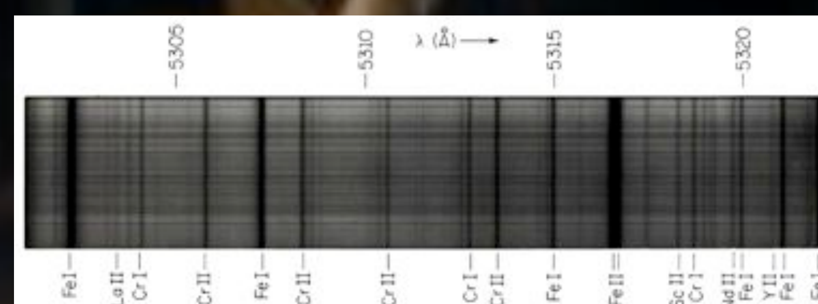
She studied botany, physics and chemistry at Cambridge

Cecilia then moved to US to pursue her studies at Radcliffe College, a coordinate college of Harvard University

A pioneer



In her 1927 Ph.D. thesis (the first in astronomy granted at Harvard), Cecilia Payne applied for the first time the correct physics to interpret the absorption line features in the Sun's spectrum



Some of the correct physics

For a gas composed of a single atomic species:

where:

$$\frac{n_{i+1}n_e}{n_i} = \frac{2}{\Lambda^3}\frac{g_{i+1}}{g_i}\exp\left[-\frac{(\epsilon_{i+1}-\epsilon_i)}{k_B T}\right]$$

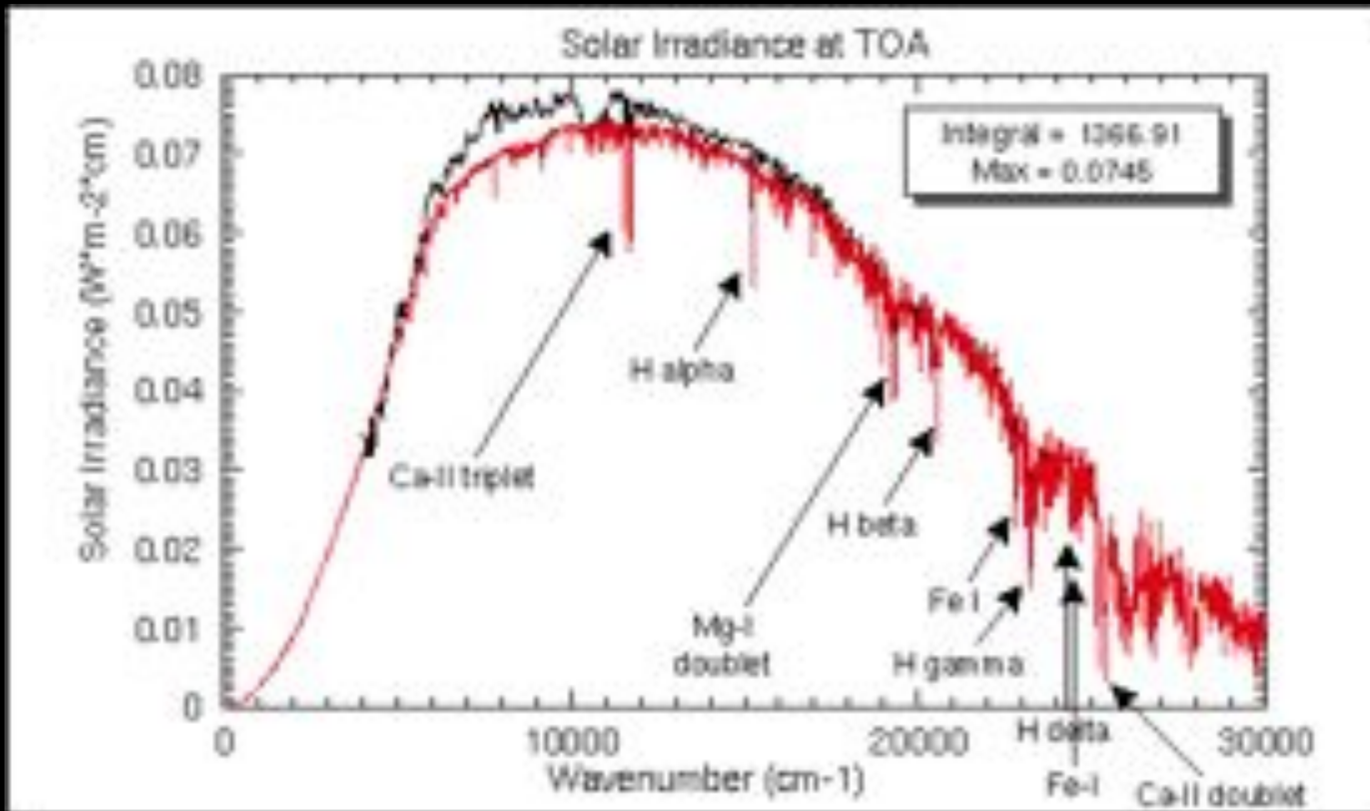
n_i *is the density of atoms in the ith state of ionization*
g_i *is the degeneracy of states for the i-ions*
ϵ_i *is the energy required to remove i electrons from a neutral atom*
n_e *is the electron density*
Λ *is the thermal de Broglie wavelength of an electron*

m_e *is the mass of an electron*
T *is the temperature of the gas*
k_B *is the Boltzmann constant*
h *is Planck's constant*

$$\Lambda \stackrel{\text{def}}{=} \sqrt{\frac{h^2}{2\pi m_e k_B T}}$$

$$\frac{n_e^2}{n-n_e} = \frac{2}{\Lambda^3}\frac{g_1}{g_0}\exp\left[\frac{-\epsilon}{k_B T}\right]$$

if only one level of ionisation is important so $n_1 = n_e$ and the number density $n = n_0 + n_1$, where ε is the ionisation energy



digital version of the solar spectrum

Ca-II triplet	11545, 11707, 11767
H alpha:	15237
Mg-I doublet:	19292, 19332
H beta:	20571
Fe-I:	22812
H gamma:	23039
H delta:	24380
Fe-I:	24723
Ca-II doublet:	25202, 25426

Balmer Series, n = 2,3,4,5...

27427*(1 – 4/n^2)

= 27430 * (5/9, 3/4, 21/25, 8/9)

= 15237,20570,23039,24380

A pioneer

Payne showed that the Sun and stars all have similar chemical compositions, and that the Sun has extremely high concentrations of hydrogen and helium, despite the strong belief at the time that these were tiny constituents compared to iron

A star of the stage

Fig. 33. Scene from The (Observatory) Pinafore, as performed on December 31, 1929. Left to right: "Prof. Rogers" (Percy M. Millman); "Josephine" (Cecilia H. Payne); "Lady computers" (Henrietta Swope, Mildred Shapley, Helen B. Sawyer, Sylvia Mussells, Adelaide Ames); "Prof. Searle" (Leon Campbell, Sr.).

A Canadian star

A pioneer

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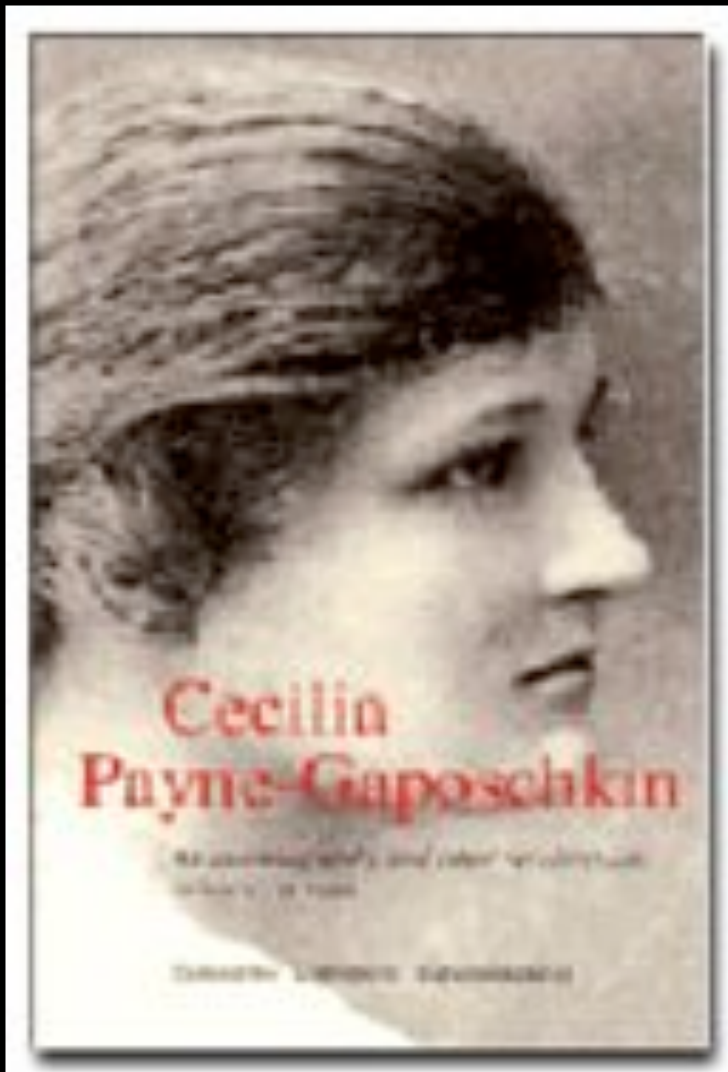
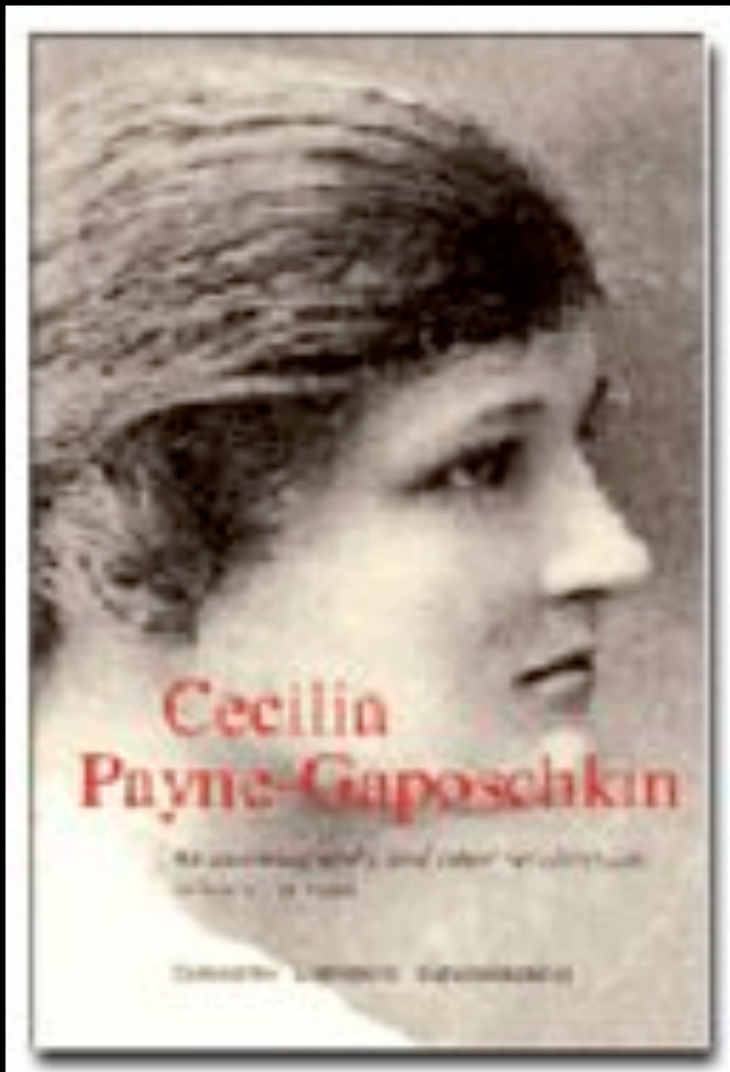
A pioneer



"The reward of the young scientist is the emotional thrill of being the first person in the history of the world to see something or to understand something.

Nothing can compare with that experience…"

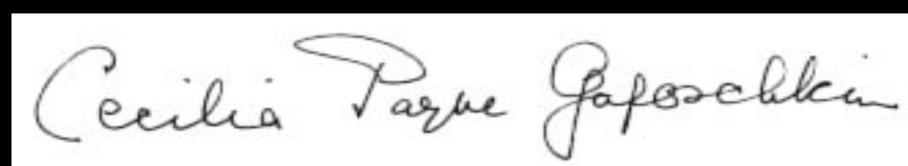
A pioneer



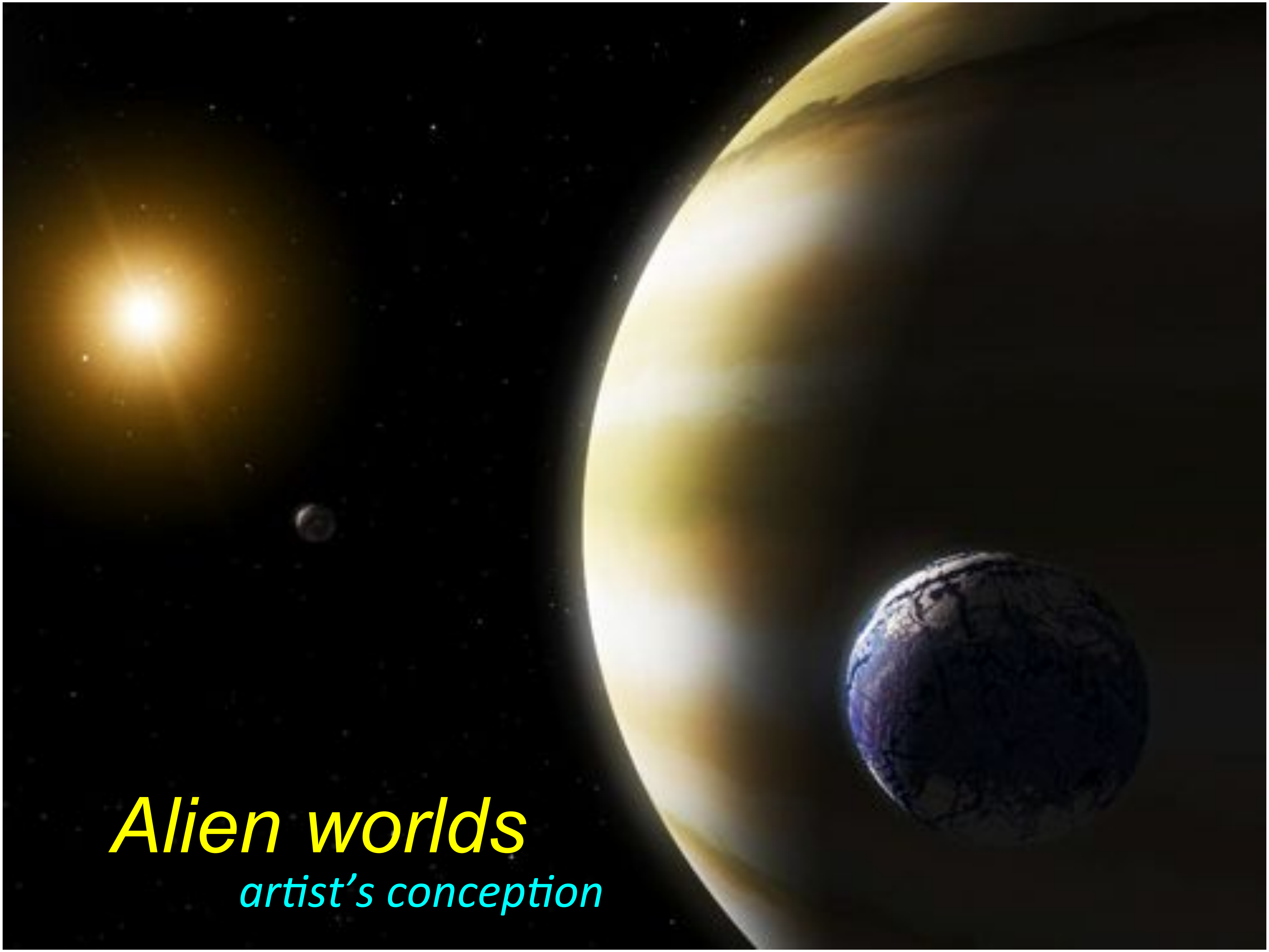
“The reward of the young scientist is the emotional thrill of being the first person in the history of the world to see something or to understand something.

Nothing can compare with that experience…

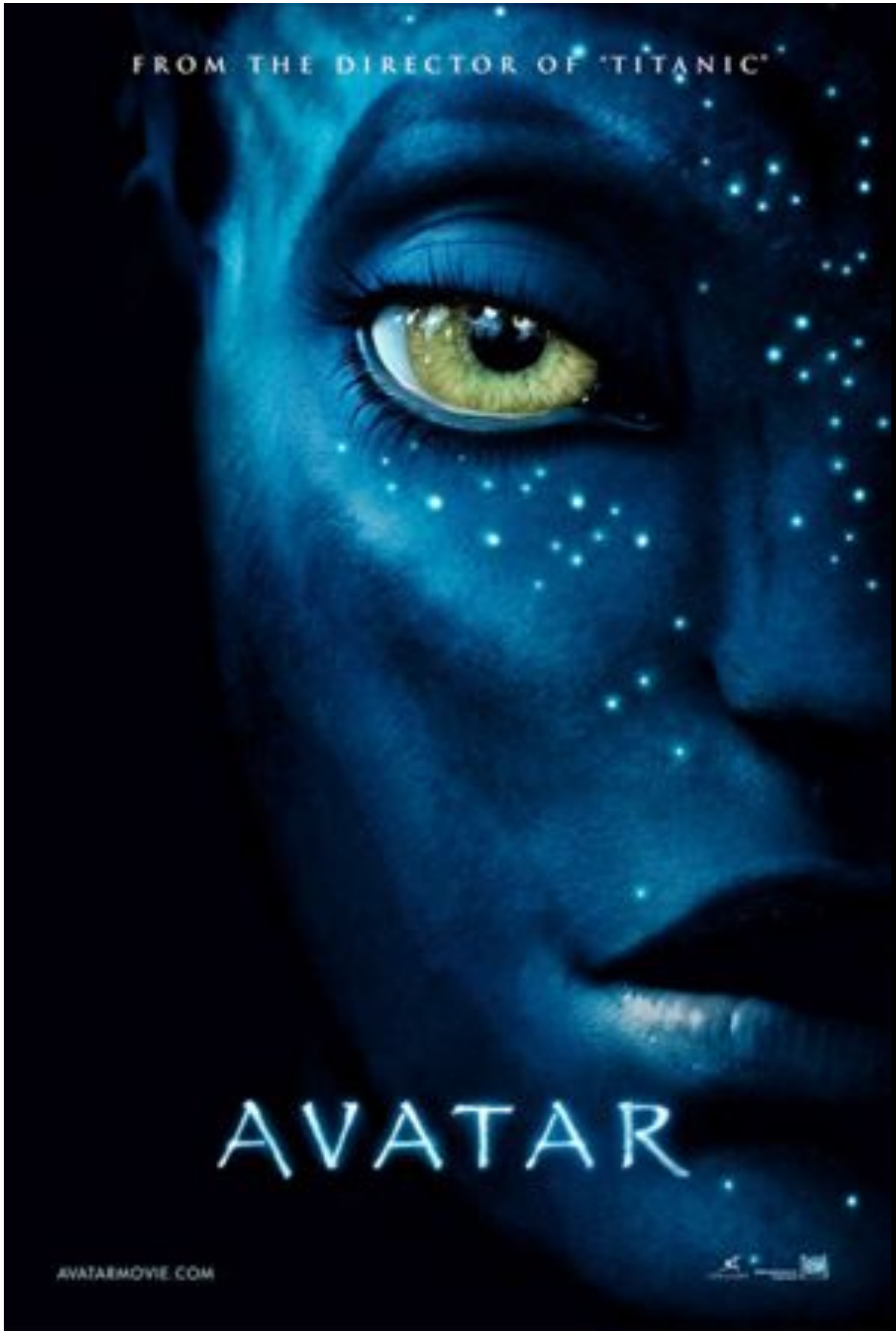
The reward of the old scientist is the sense of having seen a vague sketch grow into a masterly landscape.”



Did any questions crop up?


Alien worlds
artist's conception


Alien worlds like Pandora
Cameron's conception



Now at a theatre near you

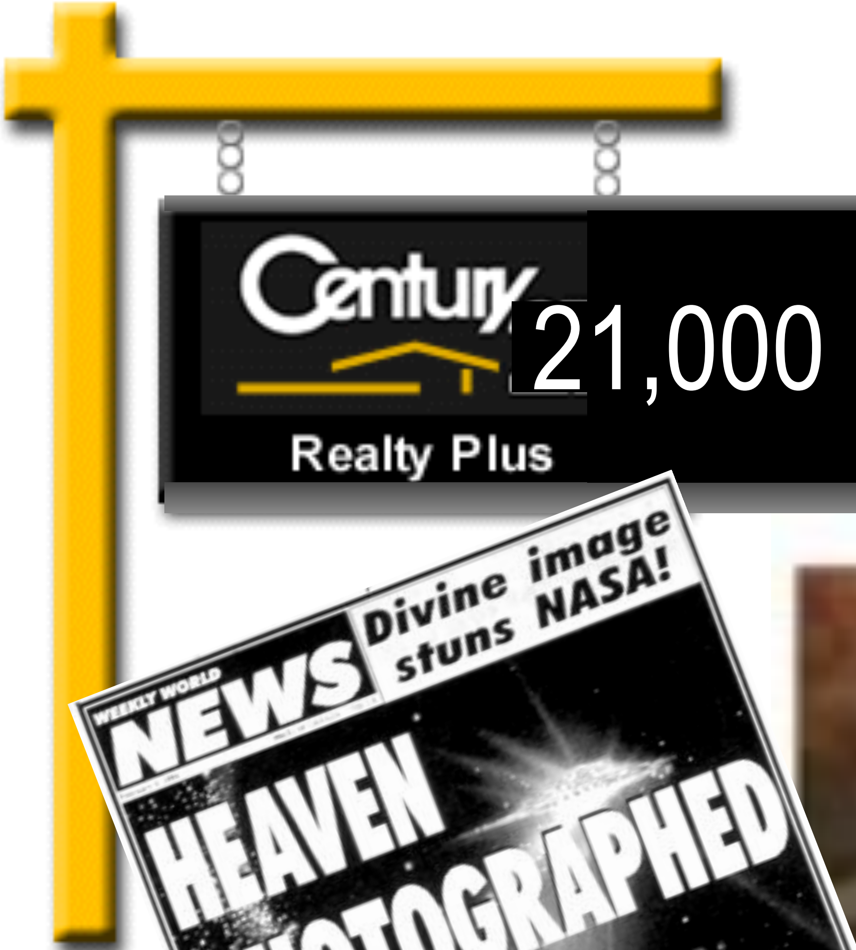
Alien worlds like Pandora

Cameron's conception


30.73
90°
60°
30°
00°
−30°
−60°
−90°
−180°
−120°
−60°
00°
60°
120°
180°
Alien worlds


Alien real estate

I've become a
real estate agent
to science fiction writers



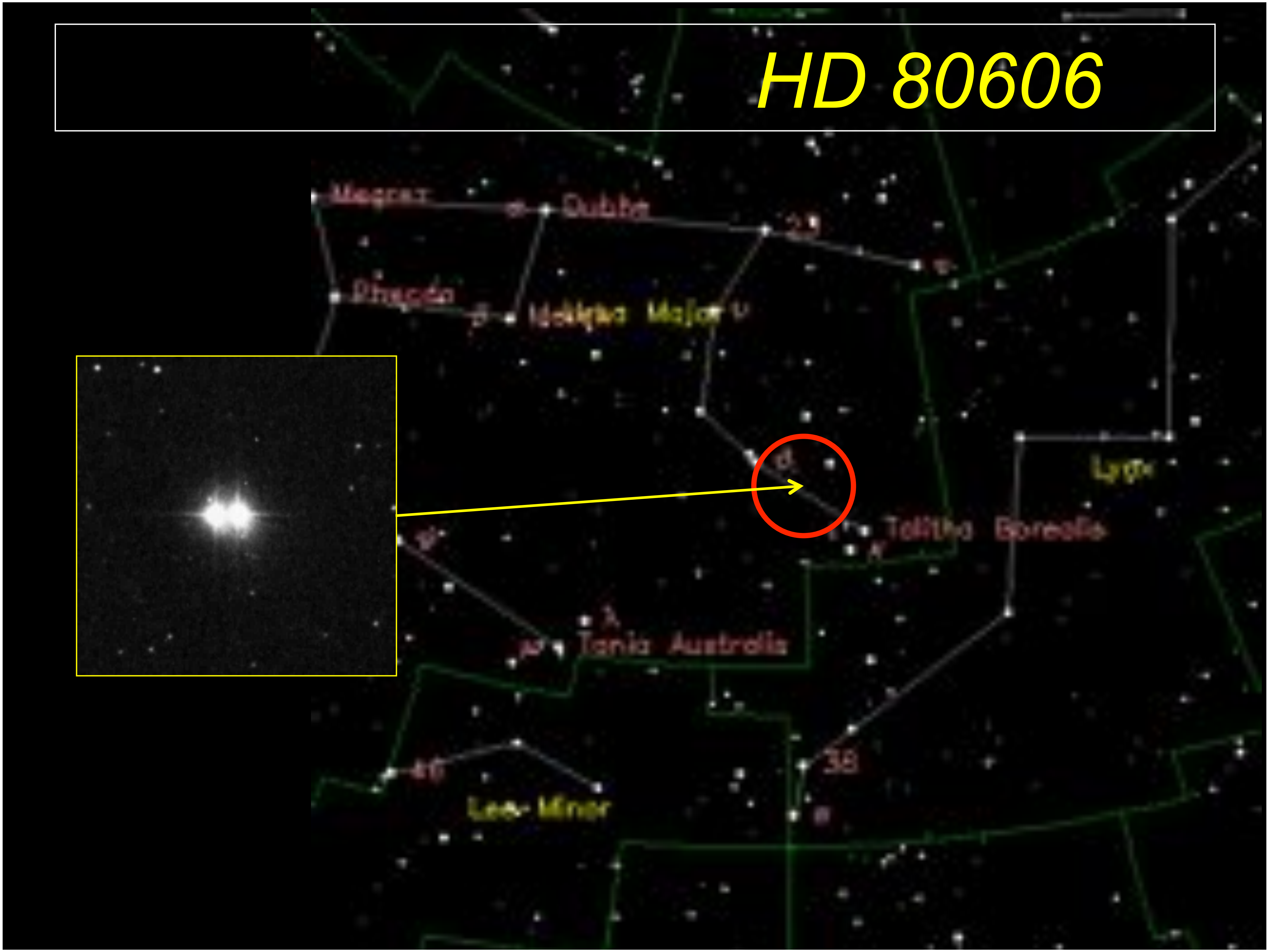

WEEKLY WORLD NEWS

Divine image stuns NASA!

HEAVEN PHOTOGRAPHED BY HUBBLE TELESCOPE

'We found where God lives,' says scientist

HD 80606

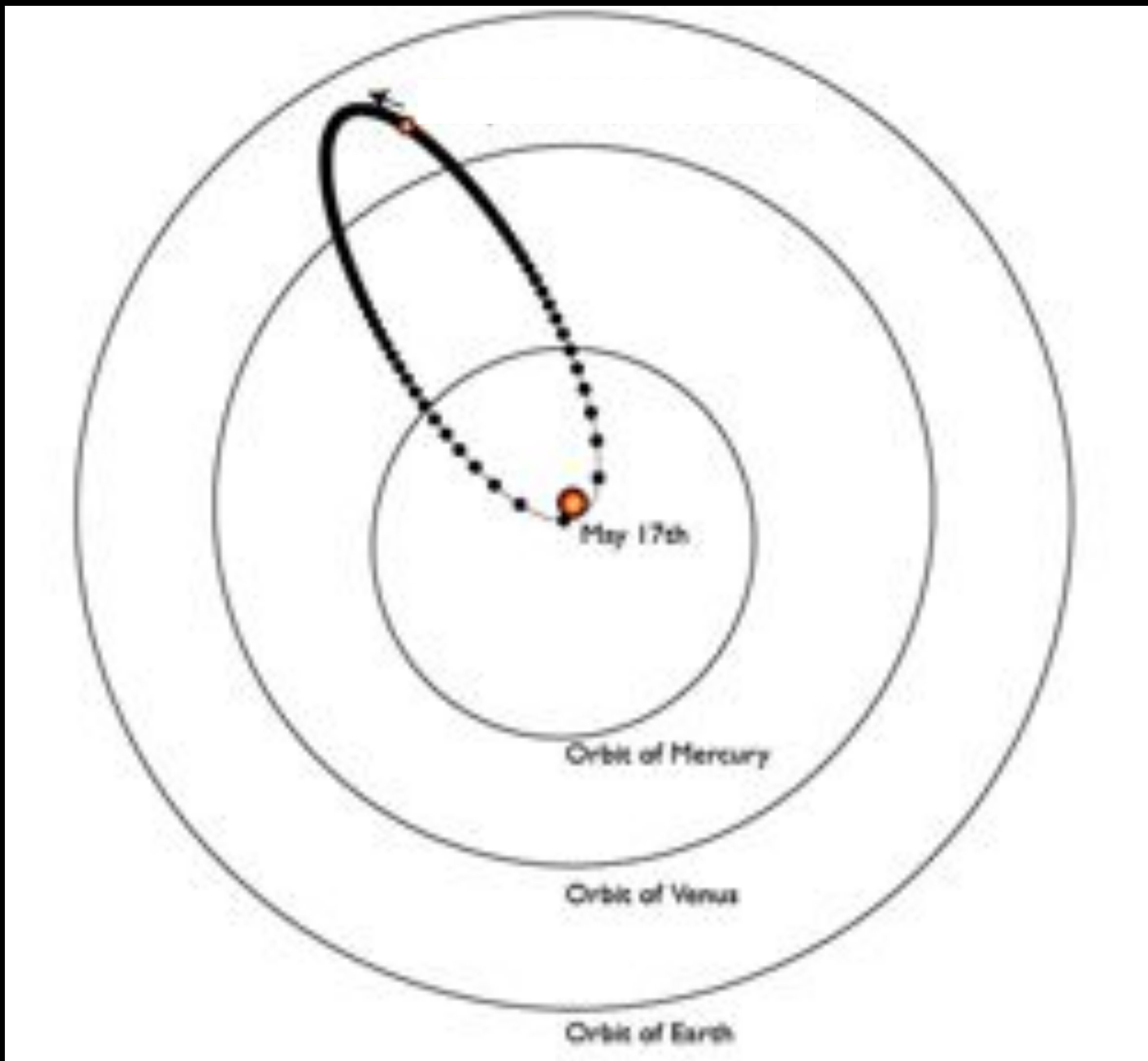


Megrez
Dubhe
23
Phecda
Ursa Major
Lynx
Talitha Borealis
Tania Australis
46
Leo Minor
38

HD 80606

Star: HD 80606
Distance from Earth: 58.38 ly
Magnitude: 8.93
Mass: 0.9 (Sun = 1)
Coordinates:
RA = 09 22 37.5679
DEC = +50 36 13.397

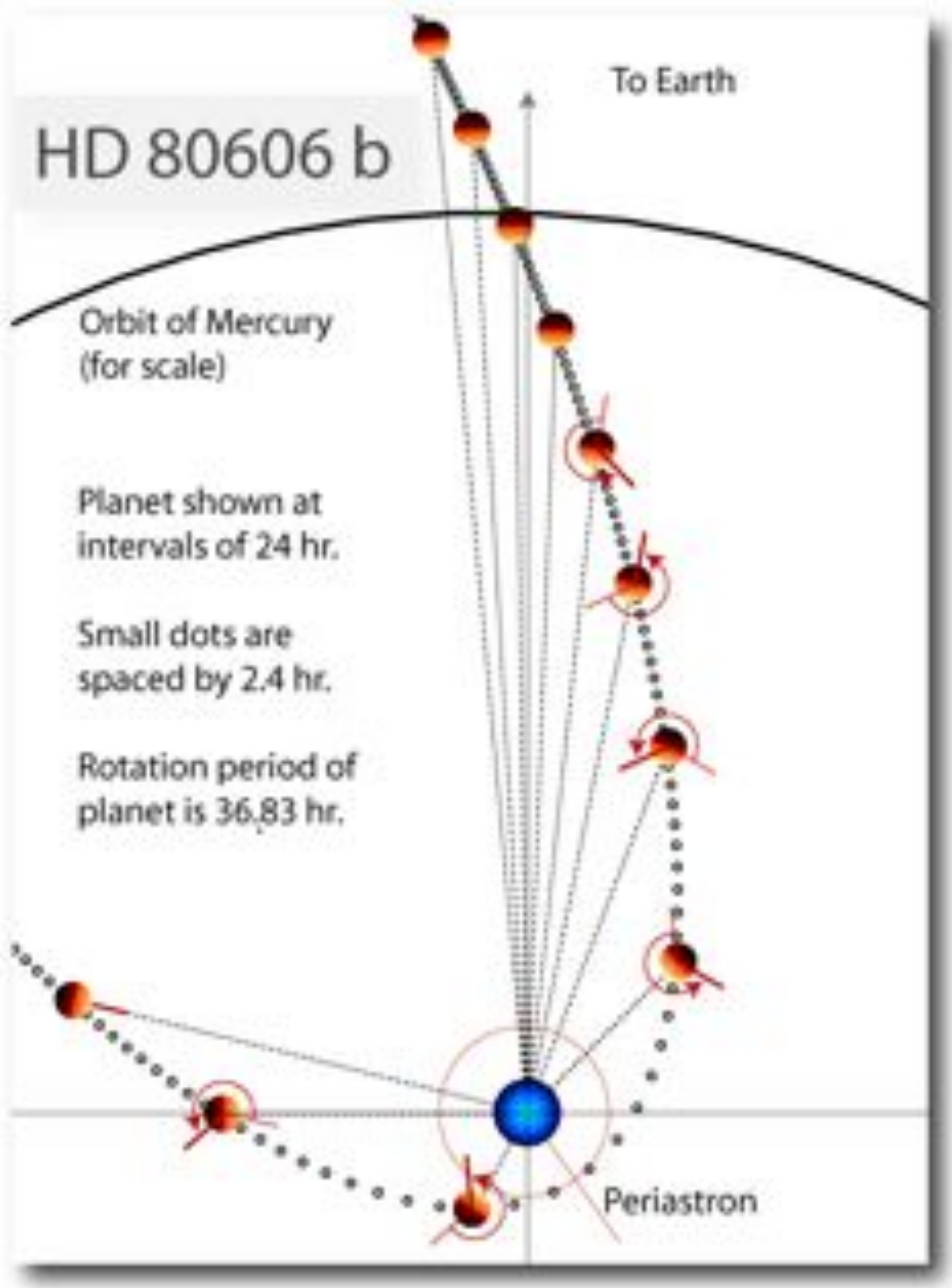
Exoplanet HD 80606 b



This planet has a very elongated orbit with a period of 112 days

The planet moves fastest when closest to the star

Its distance from the star changes dramatically in only a few days



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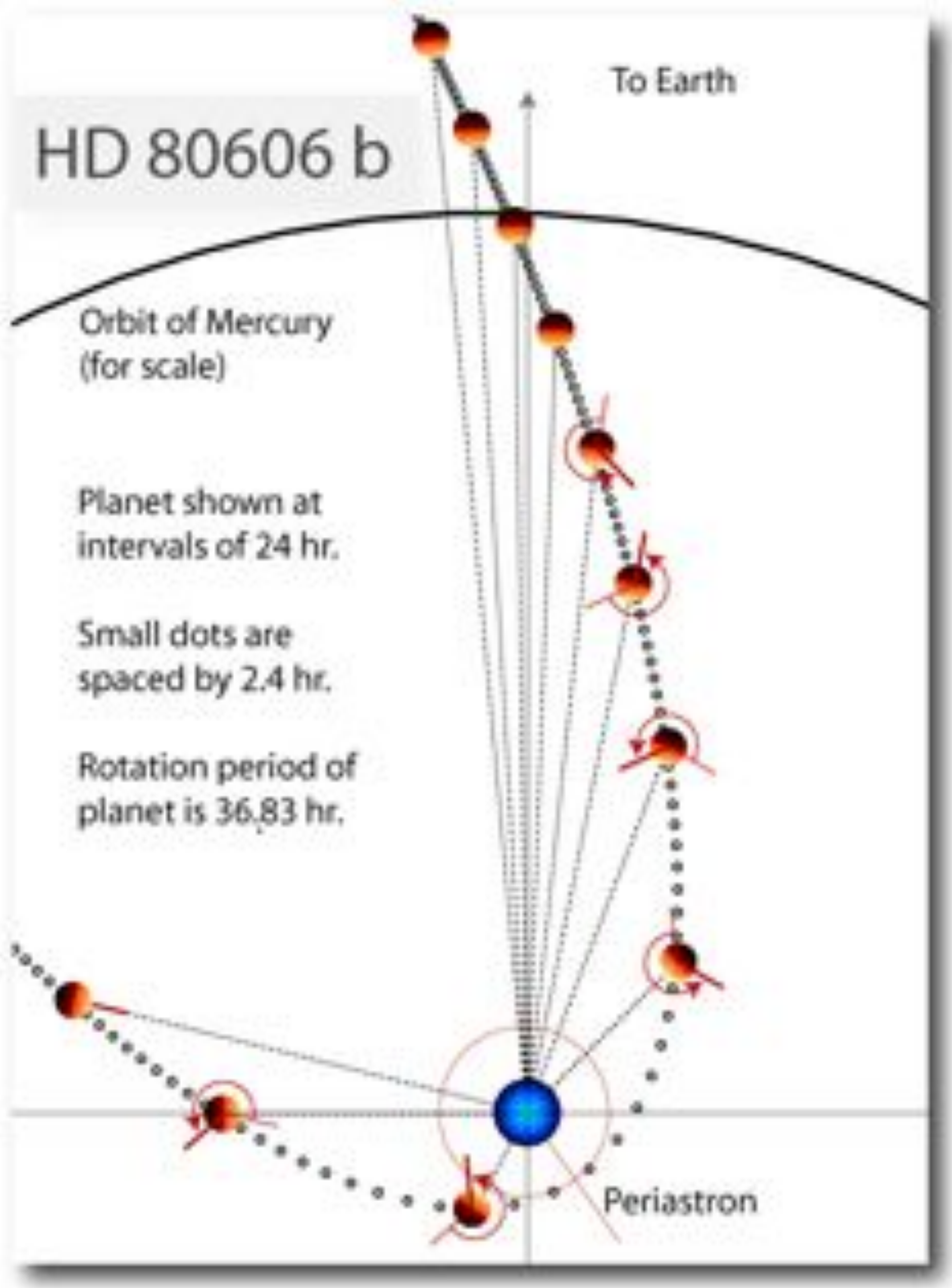
The fast change in the brightness of sunlight changes the whole planet's weather in a few hours



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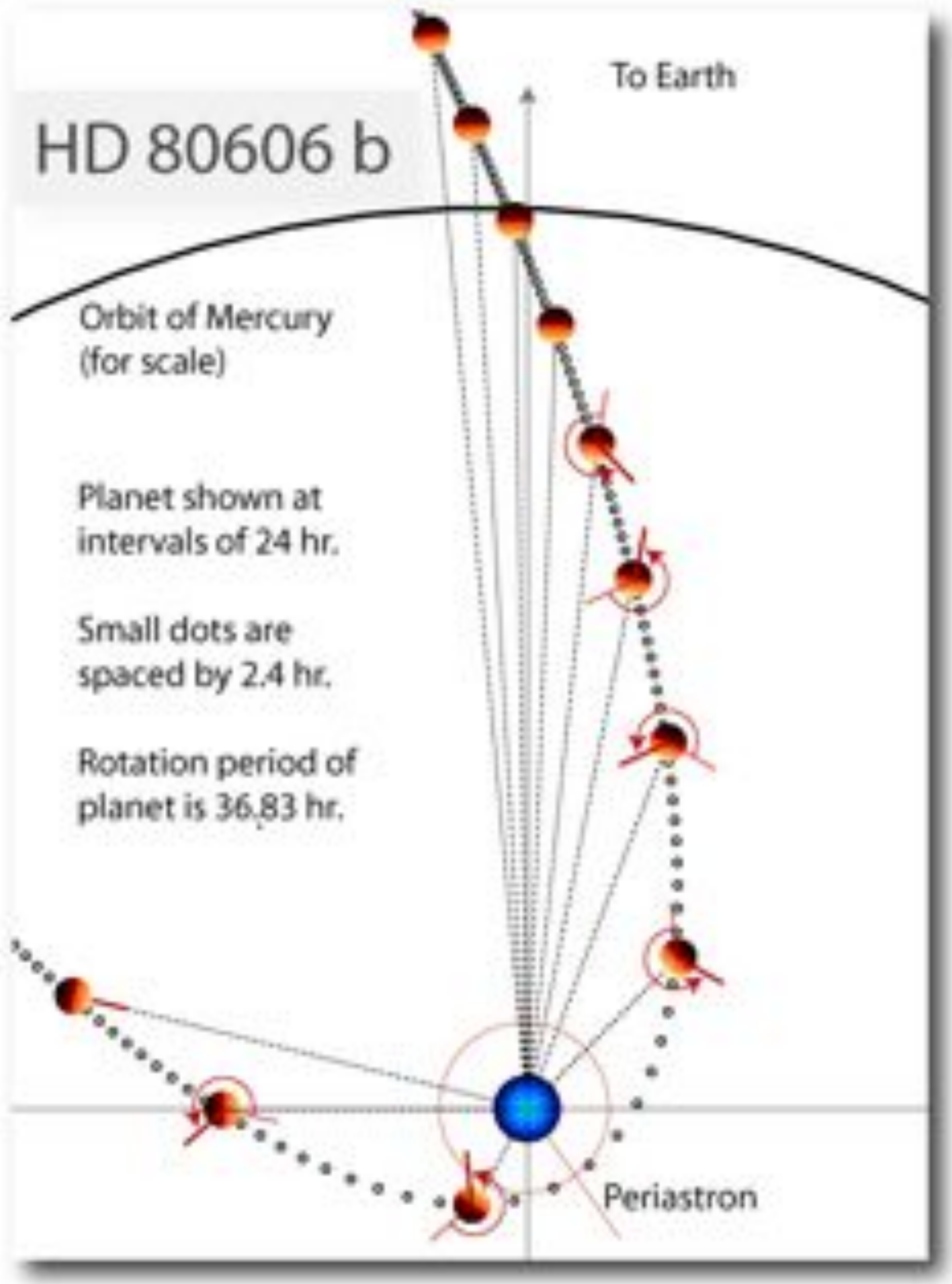
Climate change? A few °C in a century?



The planet moves fastest when closest to the star

Its distance from the star changes dramatically in only a few days

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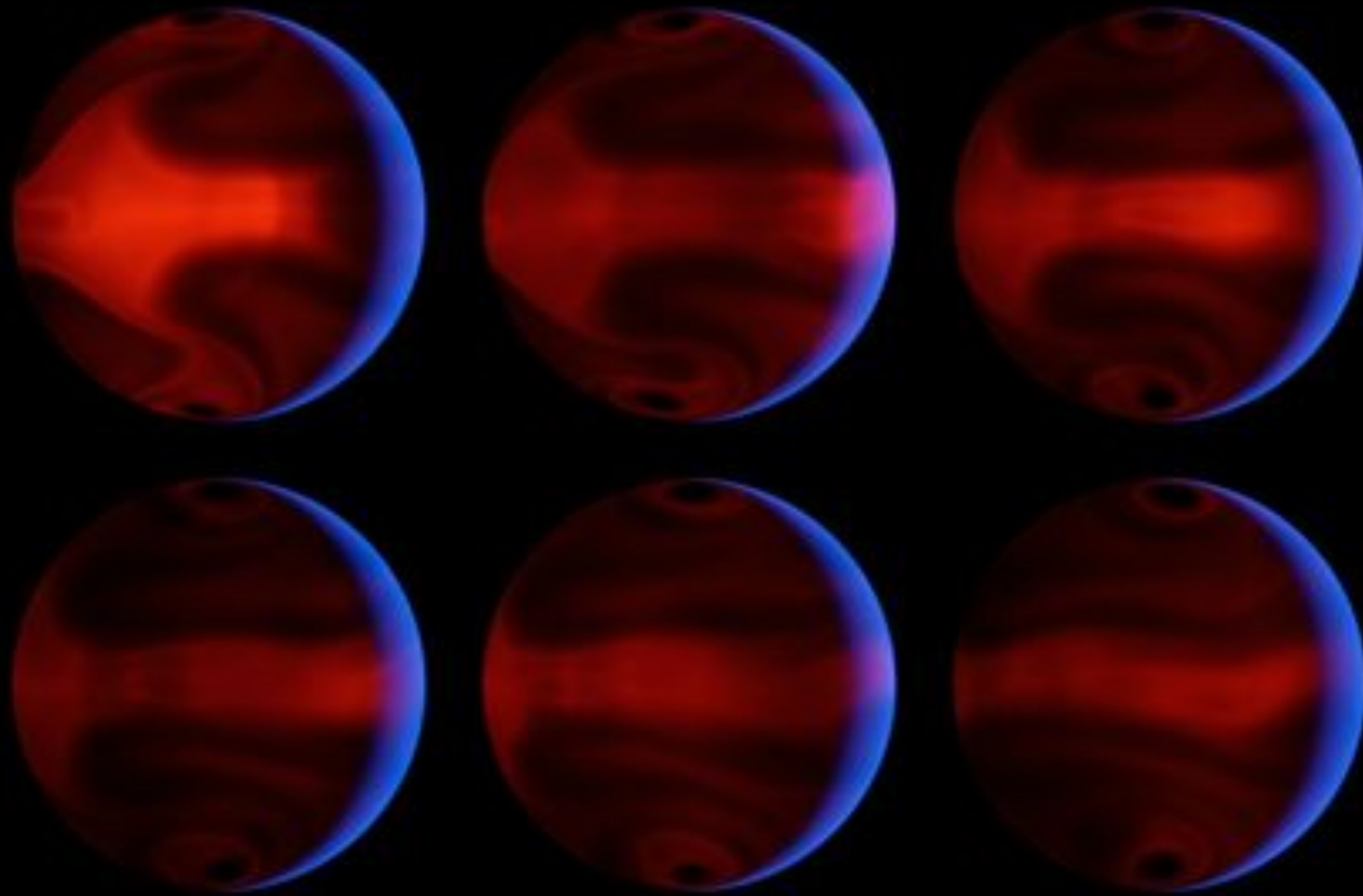
Climate change? A few °C in a century?

Try *400°C in a week!*

A climate rollercoaster

Weather on a alien world



models of atmospheric flow patterns after closest passage to the star

Alien worlds like Pandora

Cameron's conception