

# Magnetism: from compass to internet

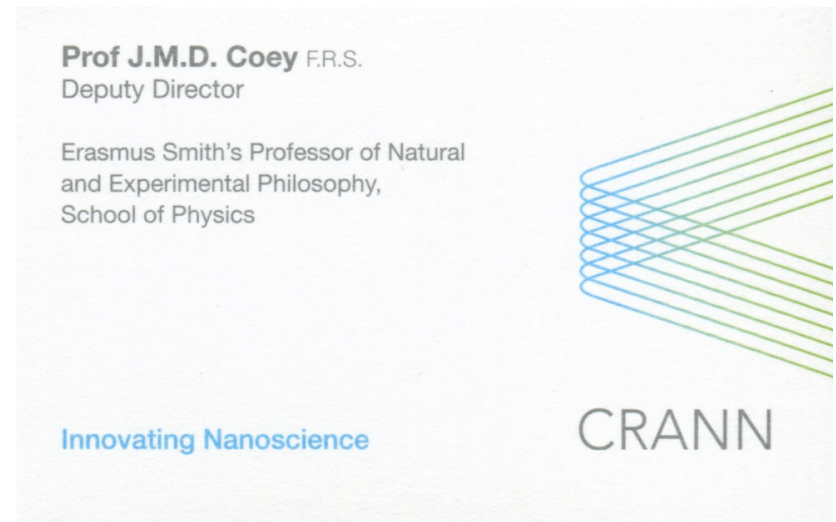
Michael Coey

Trinity College Dublin

- I. Science rules the Earth - OK?
- II. The end of an aether
- III. What the ancients knew
- IV. Billions of magnets for billions of people



Magnetism and  
Spin Electronics

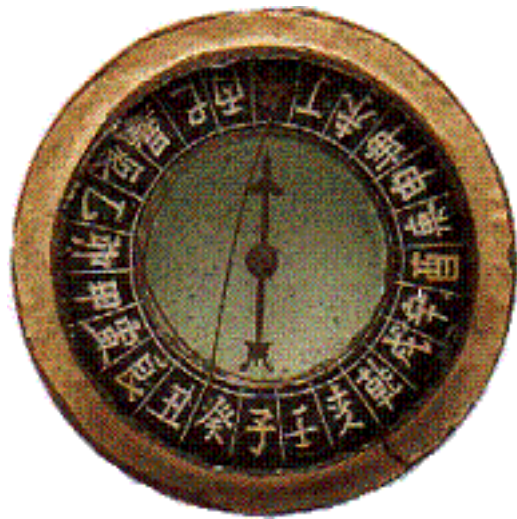






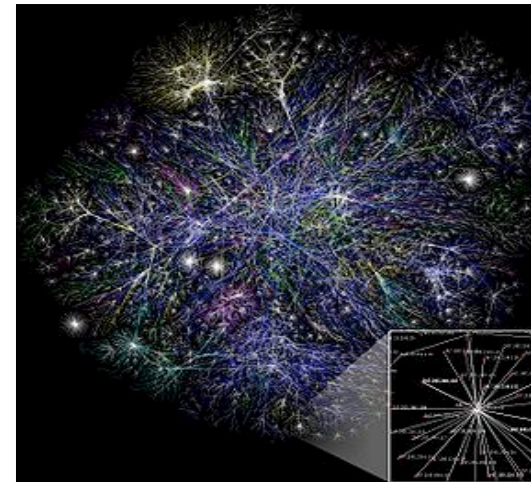


# Magnetism the Big picture



1,000 years

3,500,000,000 years





***The first 3.5 Ga.***





1	1	one	x
10	10	ten	
10 <sup>2</sup>	100	hundred	
10 <sup>3</sup>	1000	thousand	kx kilo
10 <sup>4</sup>	10000	ten thousand	
10 <sup>5</sup>	100000	hundred thousand	
10 <sup>6</sup>	1000000	million	Mx mega
10 <sup>7</sup>	10000000	ten million	
10 <sup>8</sup>	100000000	hundred million	
10 <sup>9</sup>	1000000000	billion	Gx giga
10 <sup>10</sup>	10000000000	ten billion	

1	1	one	x
$10^{-1}$	0.1	tenth	
$10^{-2}$	0.01	hundredth	
$10^{-3}$	0.001	thousandth	mx milli
$10^{-4}$	0.0001	ten thousand	
$10^{-5}$	0.00001	hundred thousand	
$10^{-6}$	0.000001	millionth	$\mu$ x micro
$10^{-7}$	0.0000001	ten millionth	
$10^{-8}$	0.00000001	hundred millionth	
$10^{-9}$	0.000000001	billionth	nx nano
$10^{-10}$	0.0000000001	ten billionth	

Big bang 14 Ga

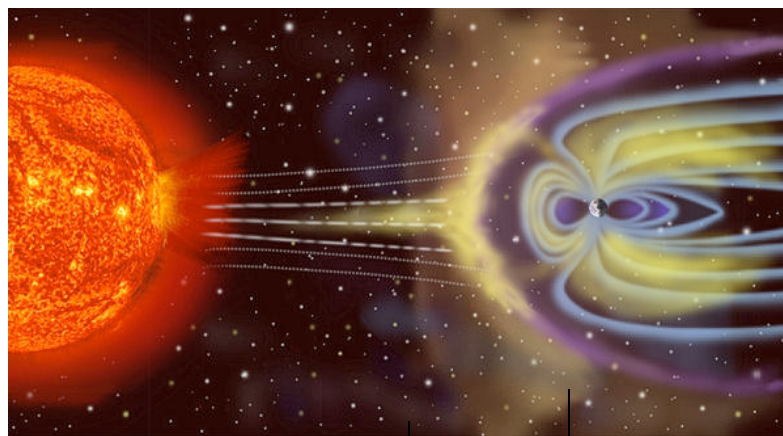


Formation of the Earth 4.5 Ga

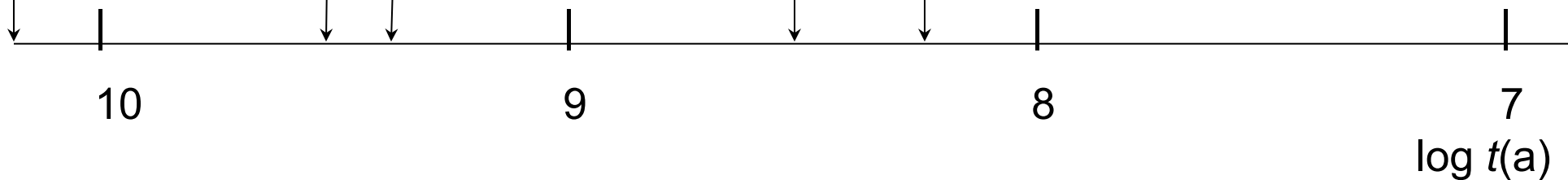


Pangaea 240 Ma

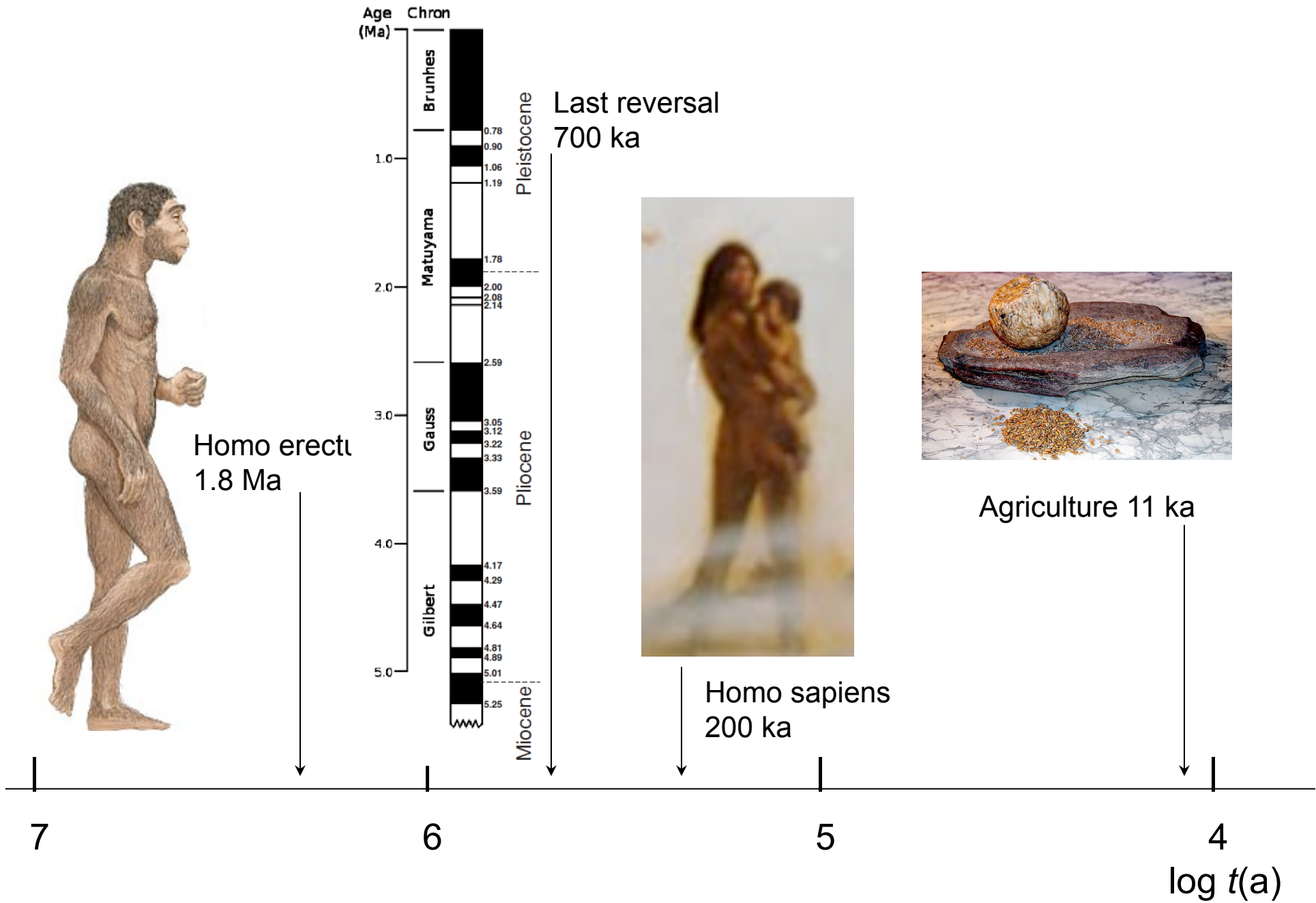
Earth's magnetic field 3.5 Ga



Magnetotactic bacteria 150 Ma









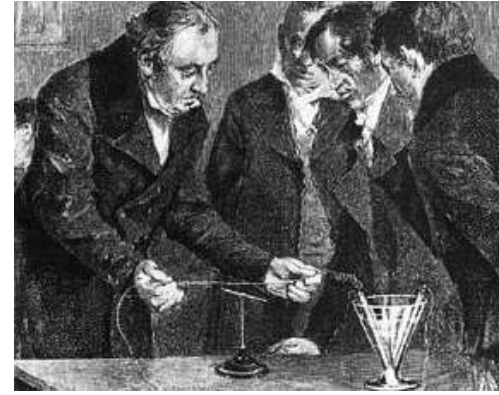
Writing 7 ka



Discovery ~3 ka



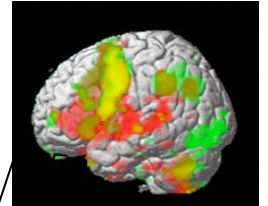
Columbus 520 a



Oersted 190 a



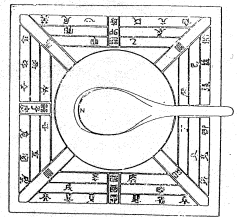
AHM 45 a



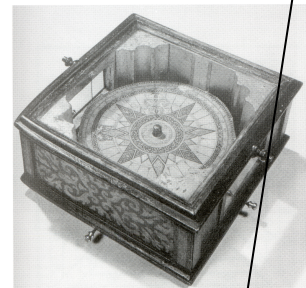
fMRI 20 a



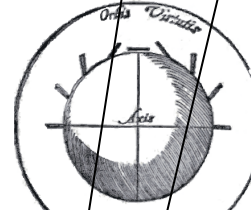
Iron metallurgy 3.8 ka



South pointer 2.2 ka



Compass 1.0 ka 410 a



De Magnete

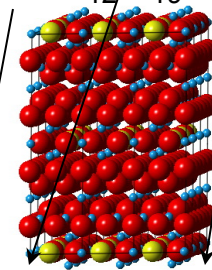


Horseshoe 250 a

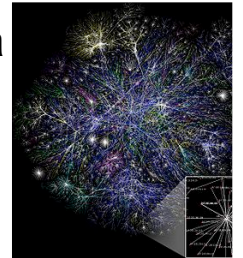
Magnetic recording 110 a



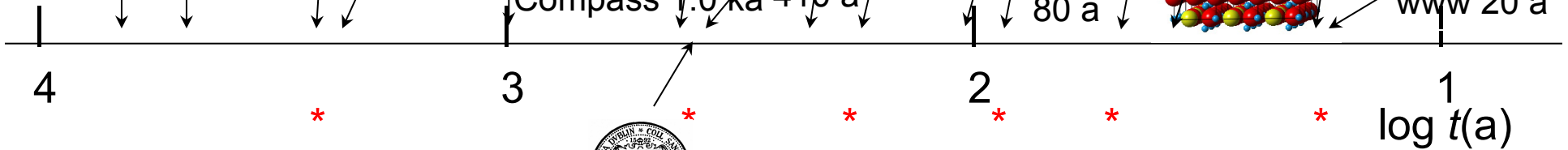
BaFe<sub>12</sub>O<sub>19</sub> 55 a



Spin 80 a



www 20 a



# 1. Science rules the Earth - OK ?

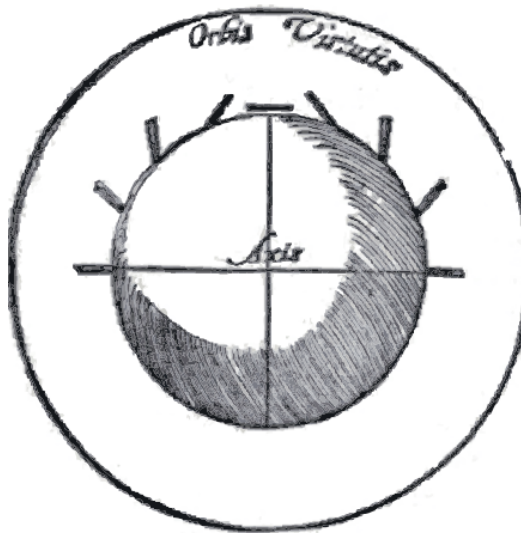
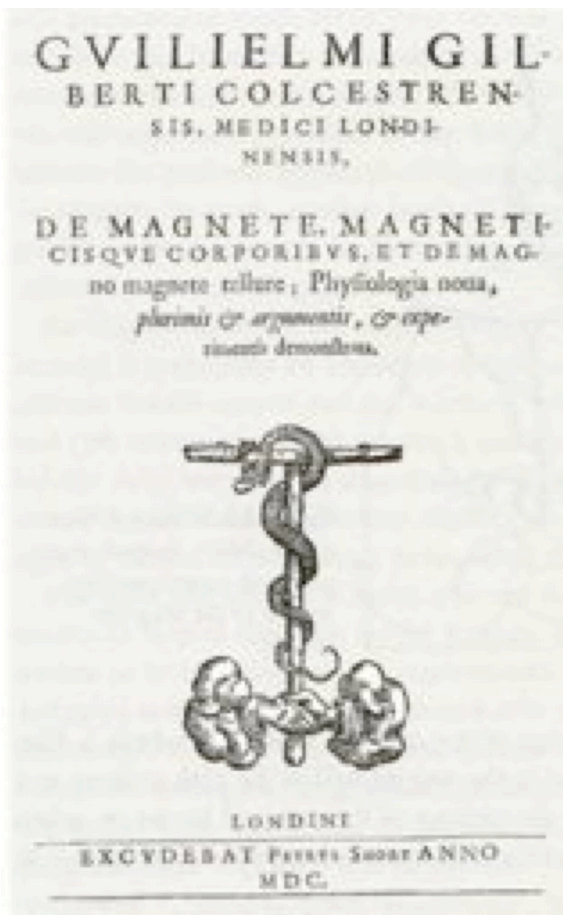
- *De Magnete* The first scientific text
- The Earth's magnetic field
- Gauss's *Magnetverein*
- Chaos - It reverses !
- The Earth moves.
- What is Science ?



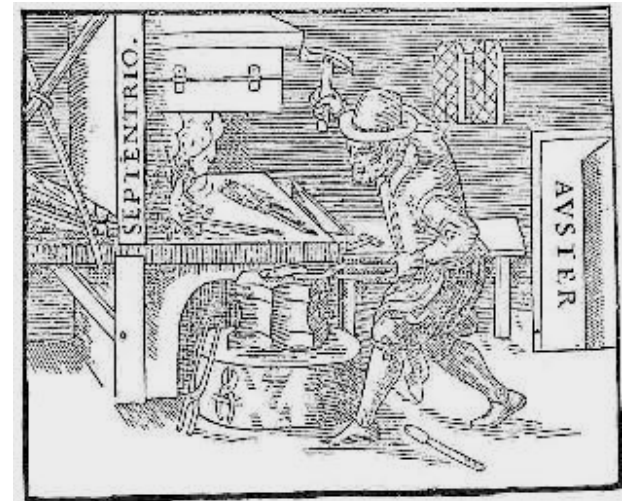
## ***1. Science rules the Earth - OK?***

Robustly polemical, but insistently evidence-based, William Gilbert's *De Magnete* (1600) was the first modern scientific text. His insight that the Earth was a great magnet and insistence that data trumps speculation led to the heroic magnetic crusade of the 1830s, an understanding of how the Earth moves by plate tectonics, sunspots, and a way to date pottery. As scientists gradually distinguished themselves from charlatans and artisans by the truth and predictive power of their magic, Galvani's animal electricity led to neurophysiology, Mesmer's animal magnetism led nowhere.

## The early modern age 1600 - 1820



Experiments on lodestone terellae led William Gilbert to conclude in 1600 that **Magnus magnes ipse est globus terrestris**



Iron is drawn to the lodestone as a bride to the bridegroom, to be embraced; as the iron is so desirous to join with it as her husband, and is so solicitous to meet the lodestone, when hindered by its weight, yet will it stand on end as if it held up its hands to beg of the stone .... But once it kissed the lodestone, as if the desire were satisfied, it is then at rest, and they are so mutually in love that if one cannot come to the other it will hang pendulous in the air.

Baptista Porta *Natural Magic* 1589

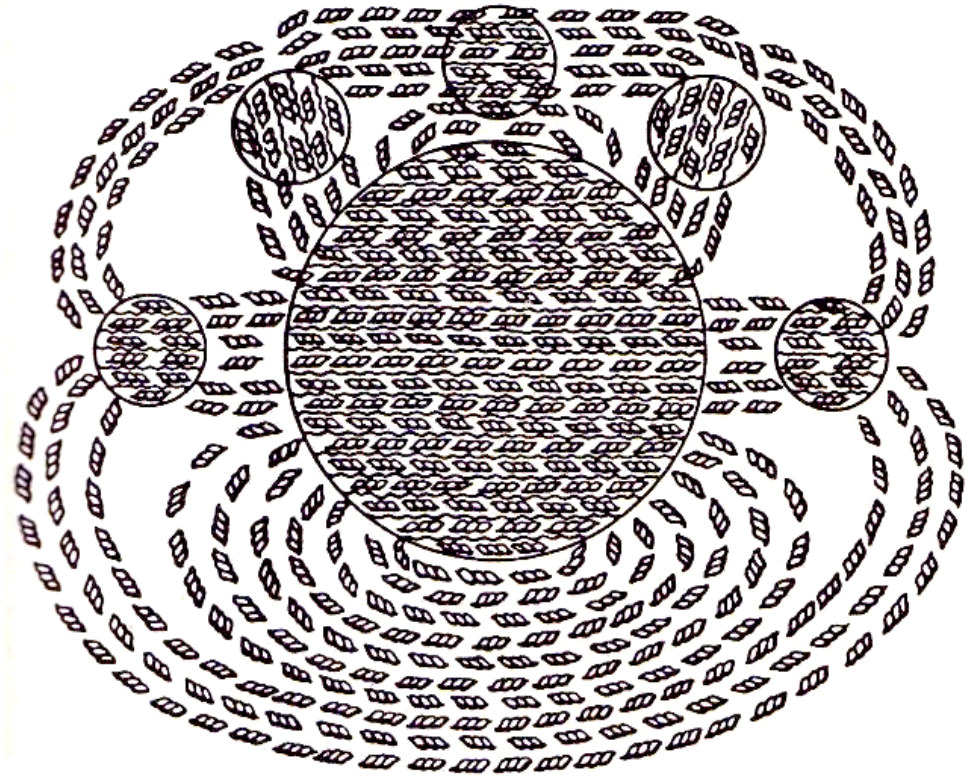
Lest the story of the lodestone should be jejeune and too brief, certain figments and falsehoods were appended. For example they asserted that a lodestone rubbed with garlic does not attract iron; now when it is in the presence of a diamond. They asserted that the lodestone placed under the head of a sleeping woman drives her out of bed if she be an adulteress..... But when the nature of the lodestone shall have been by our labours and experiments tested, then will the hidden and recondite but real causes of this great effect be brought forward, proven, shown, demonstrated ....and the foundations of a grand magnetic science being laid will appear anew, so that high intellects may no more be deluded by vain opinions.

William Gilbert *de Magnete* 1600



The Greek philosopher Thales (-600) credited the magnet with a *soul* because it could create movement - an idea that persisted for 1200 years.

Magnets were associated with the element AIR



Descartes proposed a mechanistic explanation in 1644. Effluvia threaded invisible pores of a magnetized body. **The magnet lost its soul**

Two academies, the Royal Society and the Académie des Sciences were founded in the 1660s with royal patronage to discuss natural philosophy (physical and mathematical science), based on reason and experiment.



Louis XIV



Charles II





Magnetic exploration of the Earth for much of the 18th century was motivated by the Navy's desire to solve the longitude problem



Edmond Halley led three research voyages from 1698 - 1701 to map the Earth's magnetic field.



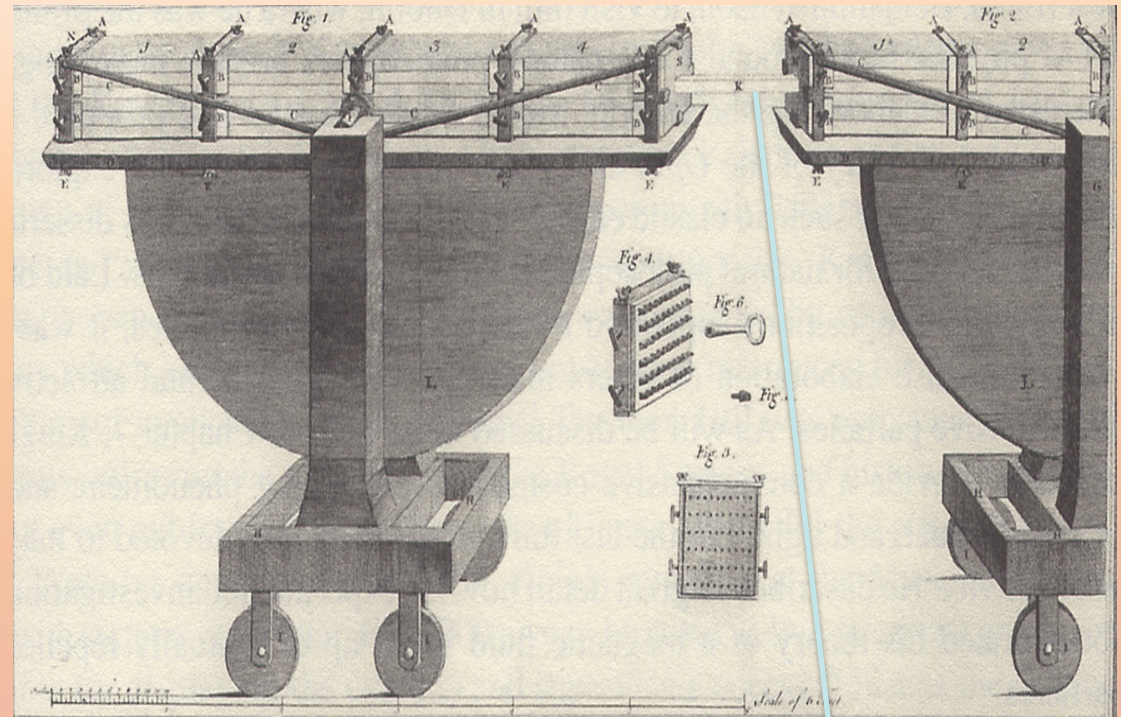


A lodestone presented to TCD in 1724 for experiments in natural philosophy.



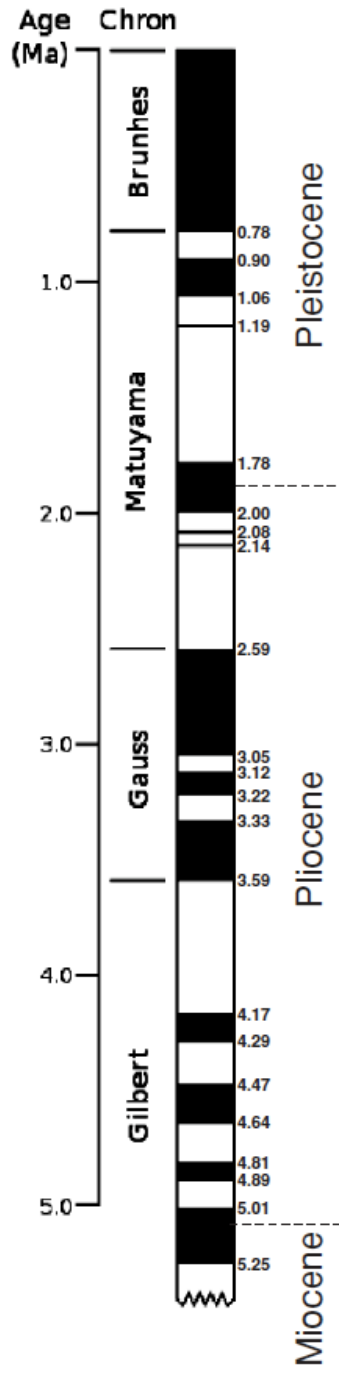


The horseshoe magnet popularized by Daniel Bernouilli in 1740 was a clever solution to the problem of self-demagnetization



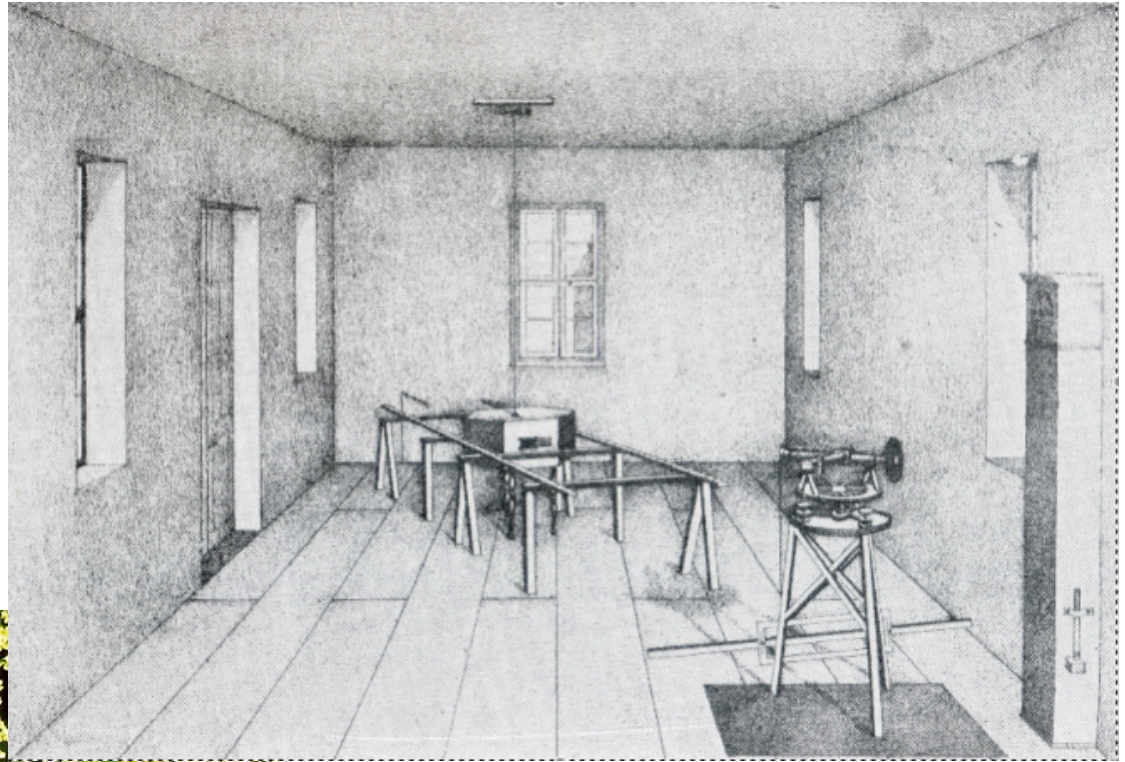
In 1760 Gowind Knight devised a method for mass production of bar magnets for the Navy. Using two wheeled magazines with 240 permanent magnets, he could rapidly magnetize a bar without any laborious stroking procedure



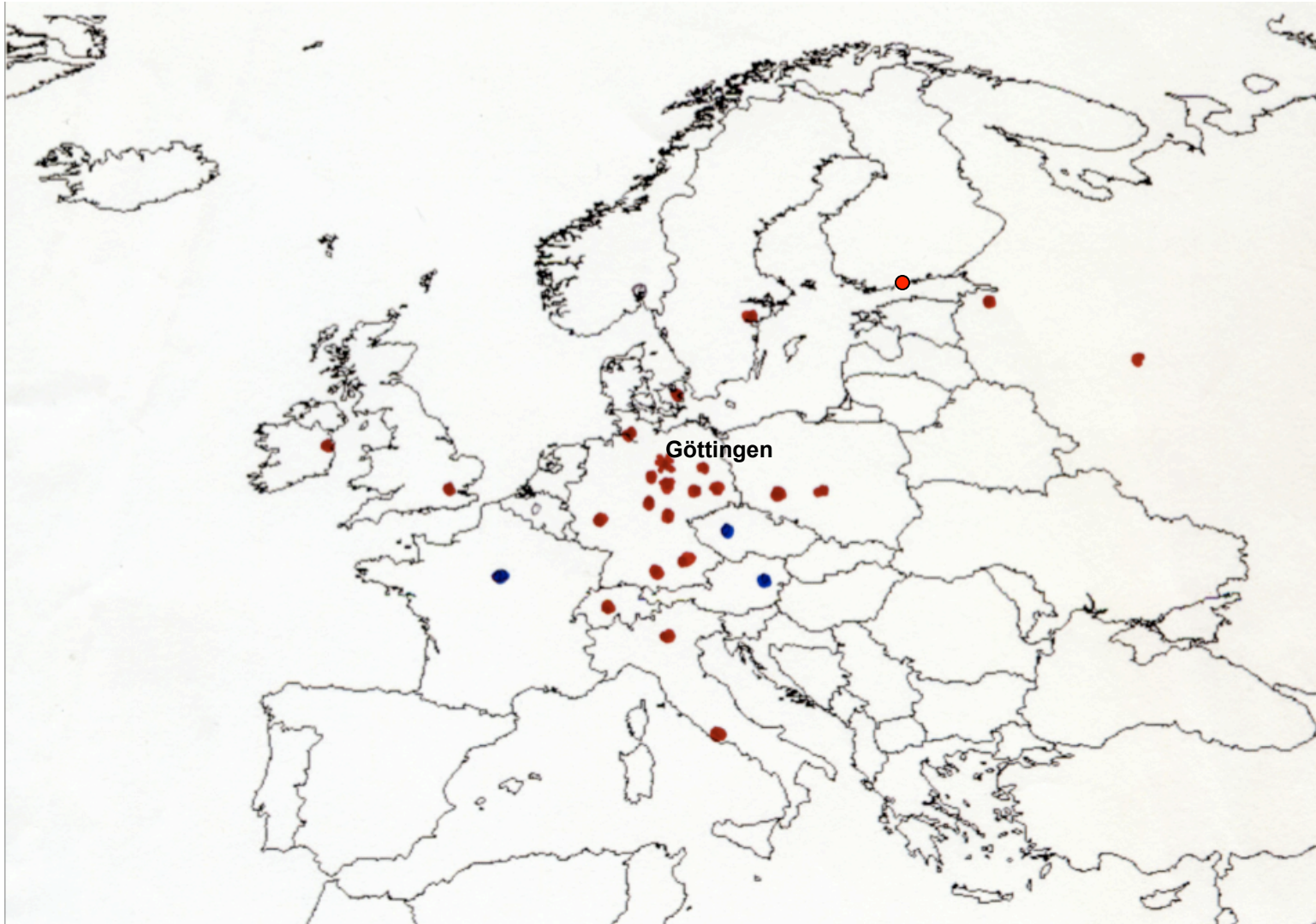




Carl Friedrich Gauss,  
1775–1855.







The Magnetische Verein  $\approx$  1836





The magnetical observatory established at Trinity College, Dublin, in 1835.

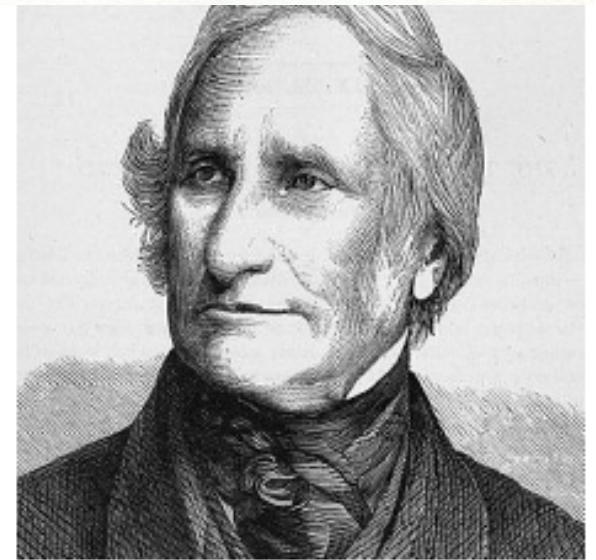


Carl Friedrich Gauss,  
1775-1855.

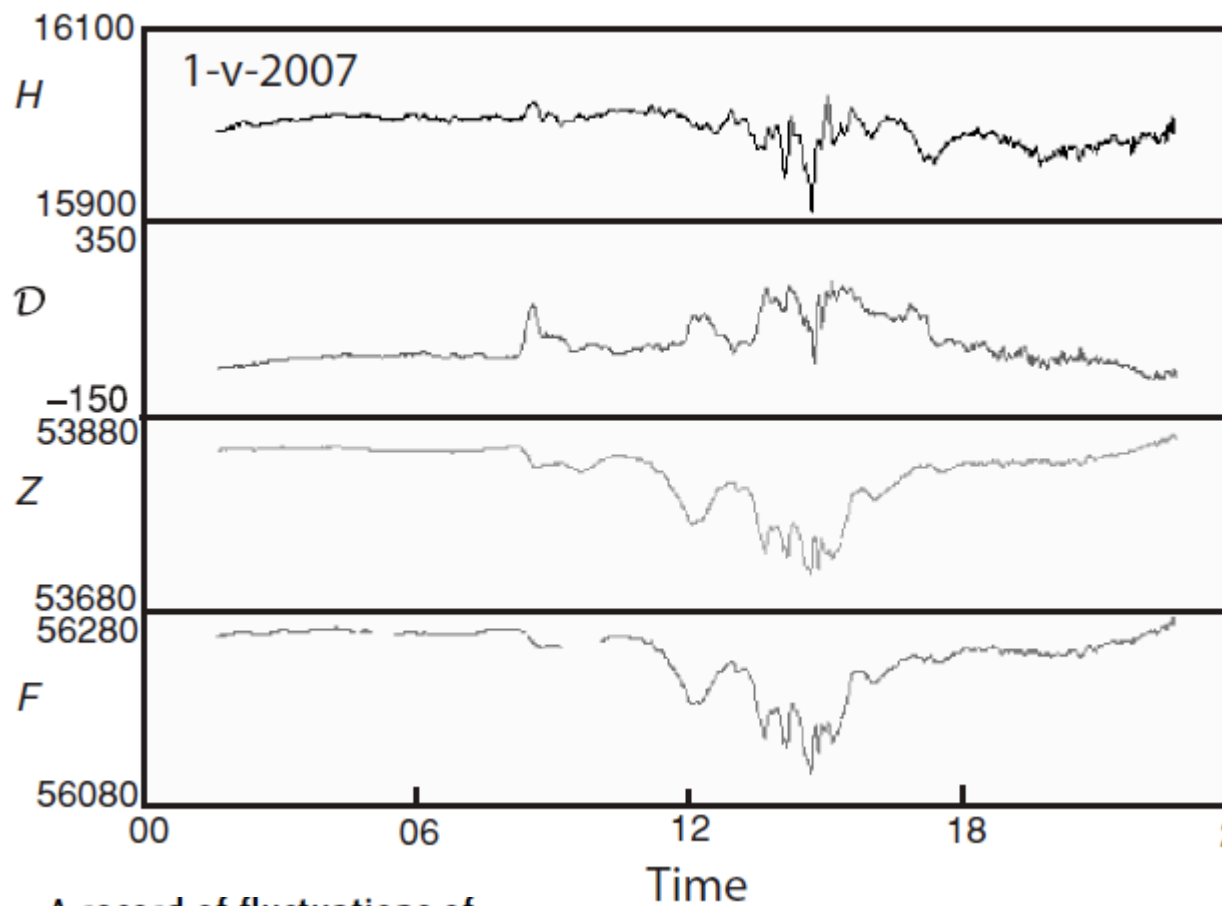
$$\nabla^2 \varphi_m = 0$$

$$\varphi_m = \sum_{l=1}^{\infty} \sum_{m=0}^l [A_l^m r^l + B_l^m r^{-(l+1)}] Y_l^m(\theta, \phi)$$

*The humblest student of astronomy, or of any other physical science if he is to profit at all by his study must in some degree go over for himself, in his own mind, if not in part with the aid of his own observation and experiment, that process of induction which leads from familiar facts to obvious laws, then to the observation of facts that are more remote and to the discovery of laws of higher orders. And even if this study be a personal act, much more must that discovery have been individual. Individual energy, individual patience, individual genius have all been needed to tear fold after fold away which hung before the shrine of nature; to penetrate gloom after gloom into those Delphic depths, and force the reluctant Sibyl to utter her oracular responses.*

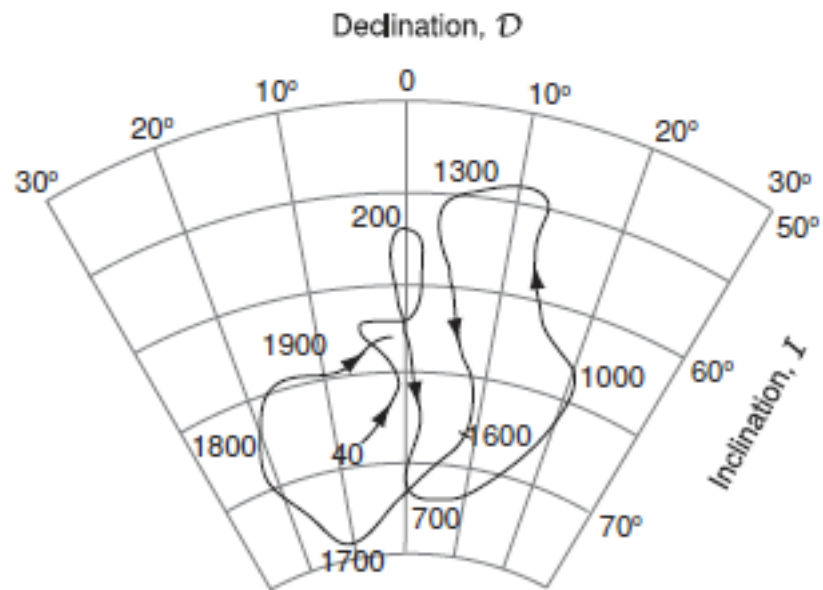


**Edward Sabine, 1788–1883.**

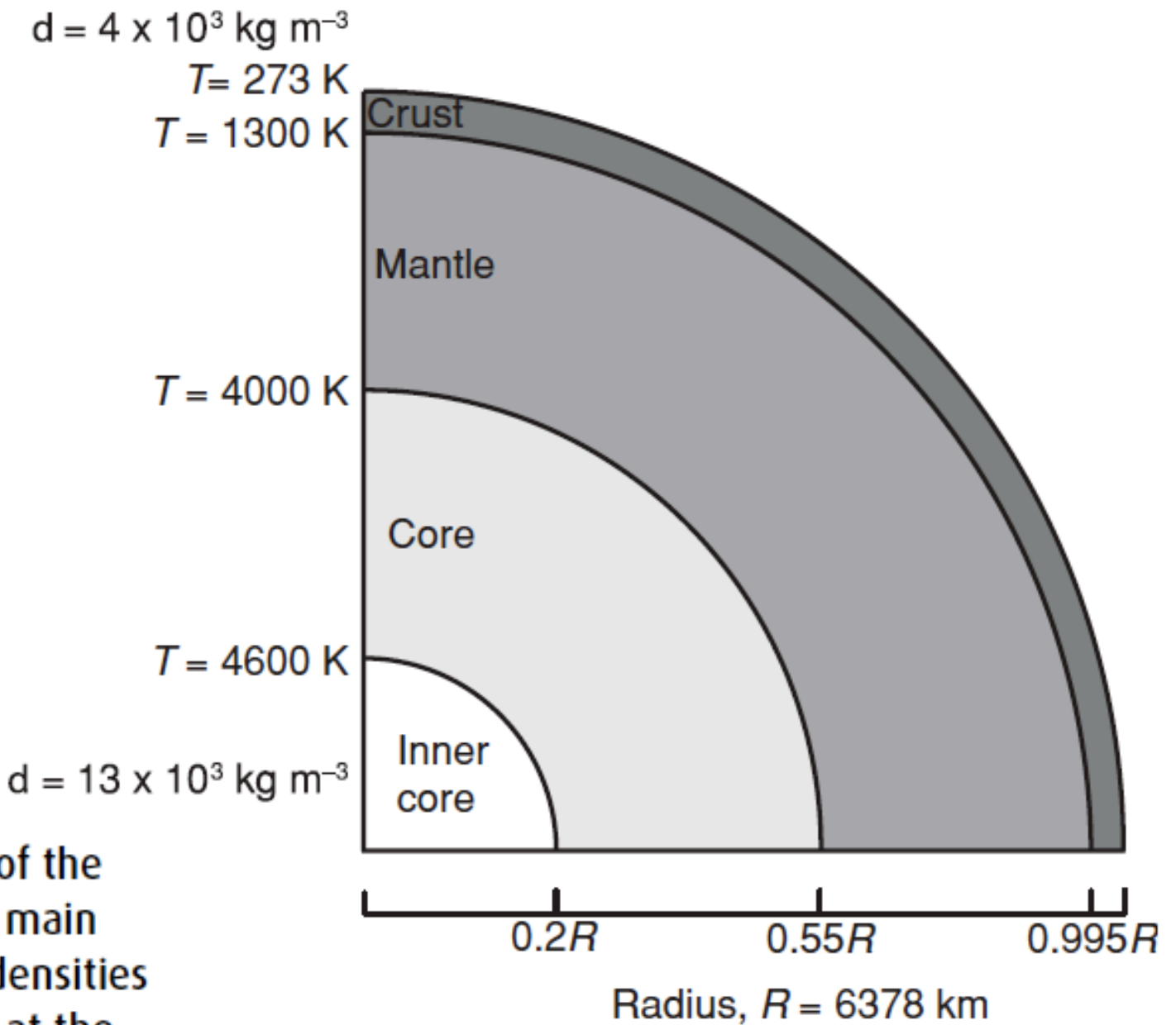


A record of fluctuations of the Earth's magnetic field, taken at Sitka in Alaska on 1 May 2007. A magnetic observatory has existed on this site since 1842. Units of  $H$ ,  $Z$  and  $F$  are nanoteslas, the units of  $D$  are degrees.

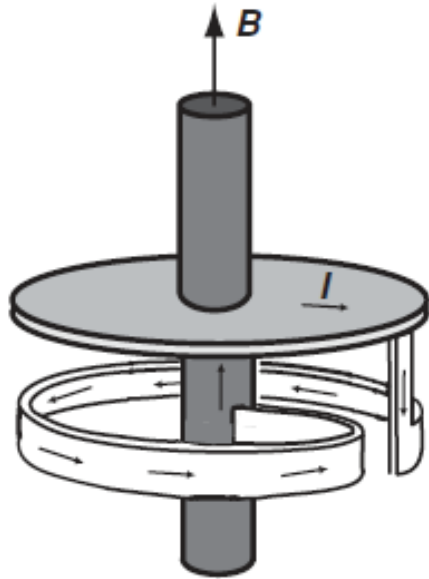




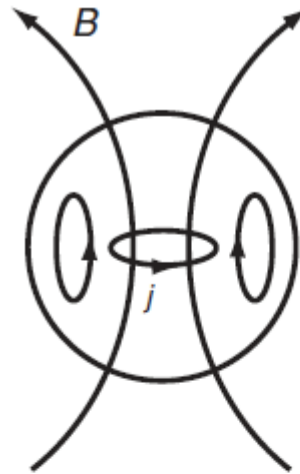
The scalar variation of the Earth's field deduced by combining observations in Paris ( $>1600$ ) with measurements of the remanence of baked clay ( $<1600$ ).



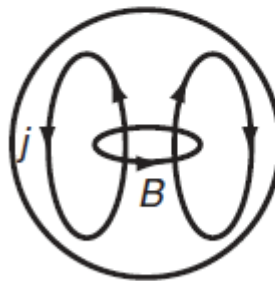
Internal structure of the Earth. Radii of the main structures, mean densities and temperatures at the centre and surface are given.



A mechanical model of a self-exciting dynamo.



Poloidal field

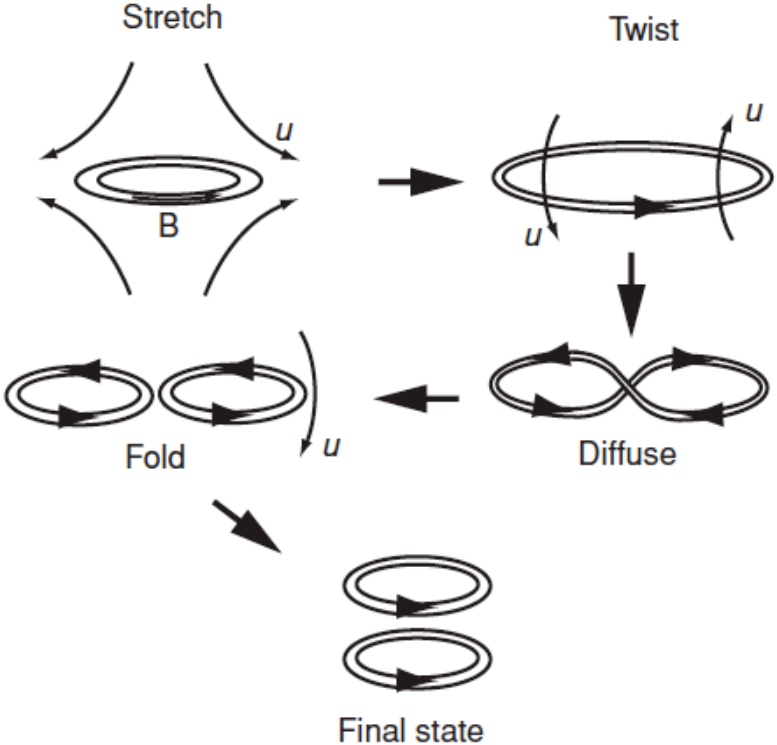


Azimuthal field

Azimuthal currents create poloidal fields, and vice versa.

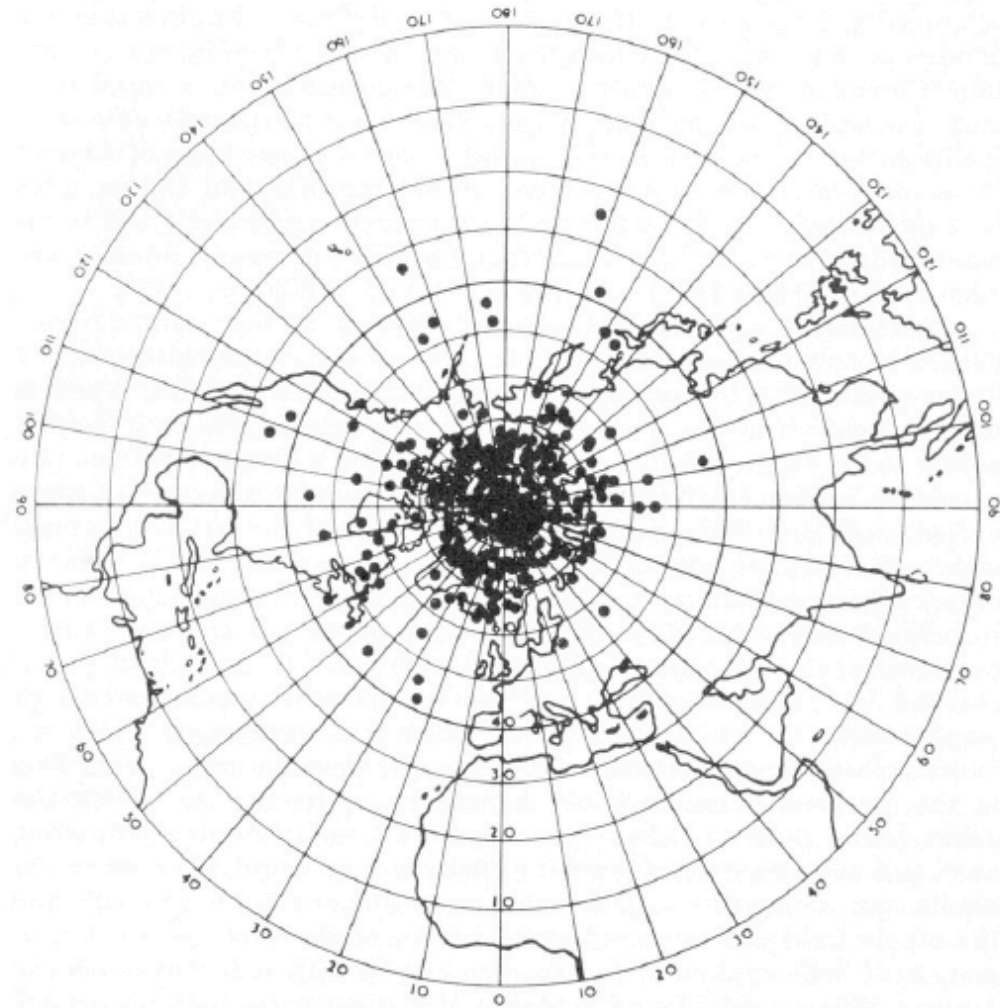


# Reynolds number



Magnetic field is intensified in a fluid core by a process of stretching and twisting flux lines.  $u$  is the fluid velocity.

Position of the Earth's magnetic pole deduced from measurements of recently formed igneous rocks. Half of the points have the present polarity, while the other half are reversed. On average the magnetic field is that of a geocentric axial dipole.



Apparent polar wander paths which are used to reconstruct the past positions of plates on the globe. Data from rocks in Europe (open circles) and North America (solid circles) can be made to coincide by closing up the Atlantic ocean.





Schematic representation of plates separating at a mid-ocean ridge. The pattern of magnetization of sea-floor basalts measured across the North Atlantic led to the ideas of seafloor spreading and global plate tectonics.

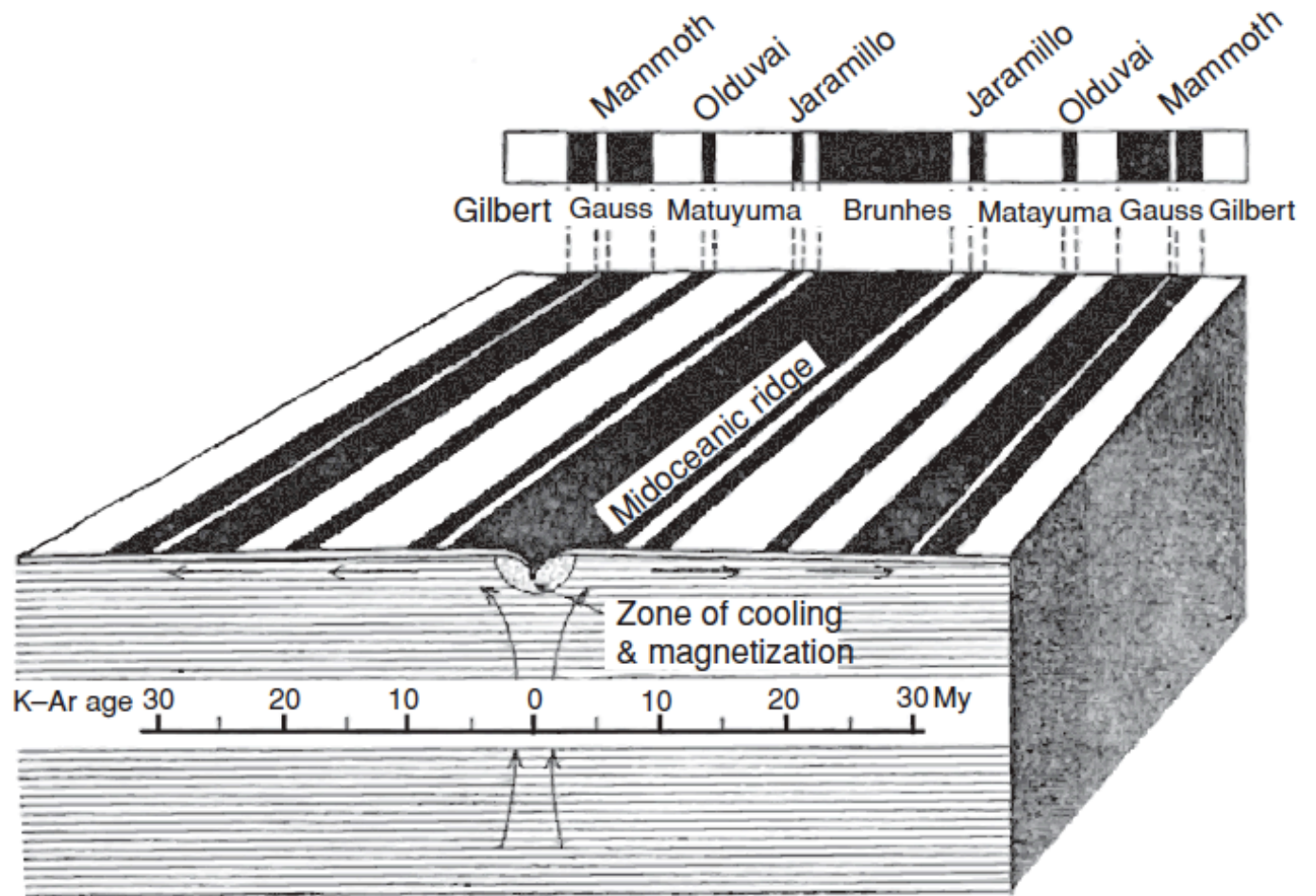
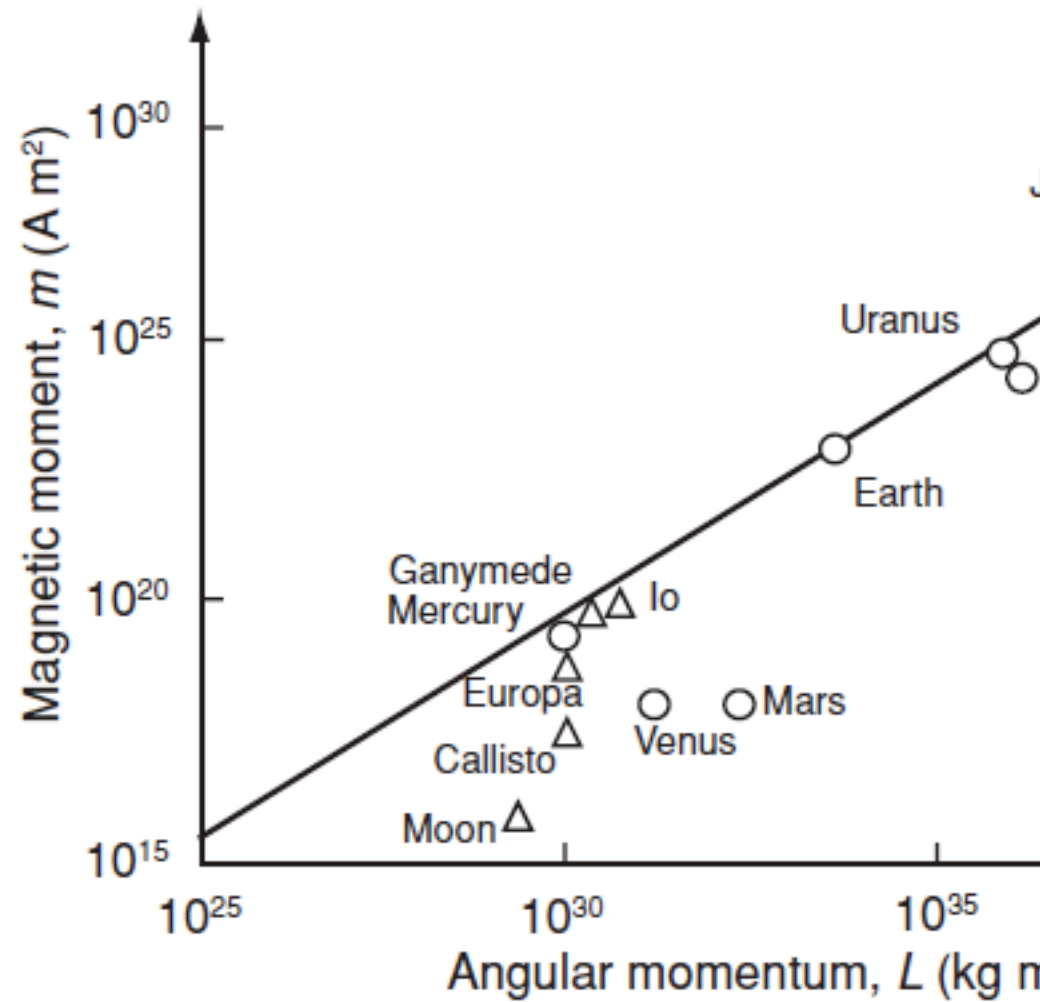


Figure 15.23

Magnetic moments of planets and moons in the solar system, plotted against their angular momentum. (After P Rochette.)



**Figure 15.24**

The internal structure of the Sun. Radii of the main structures, mean densities and temperatures at the centre and surface are given.

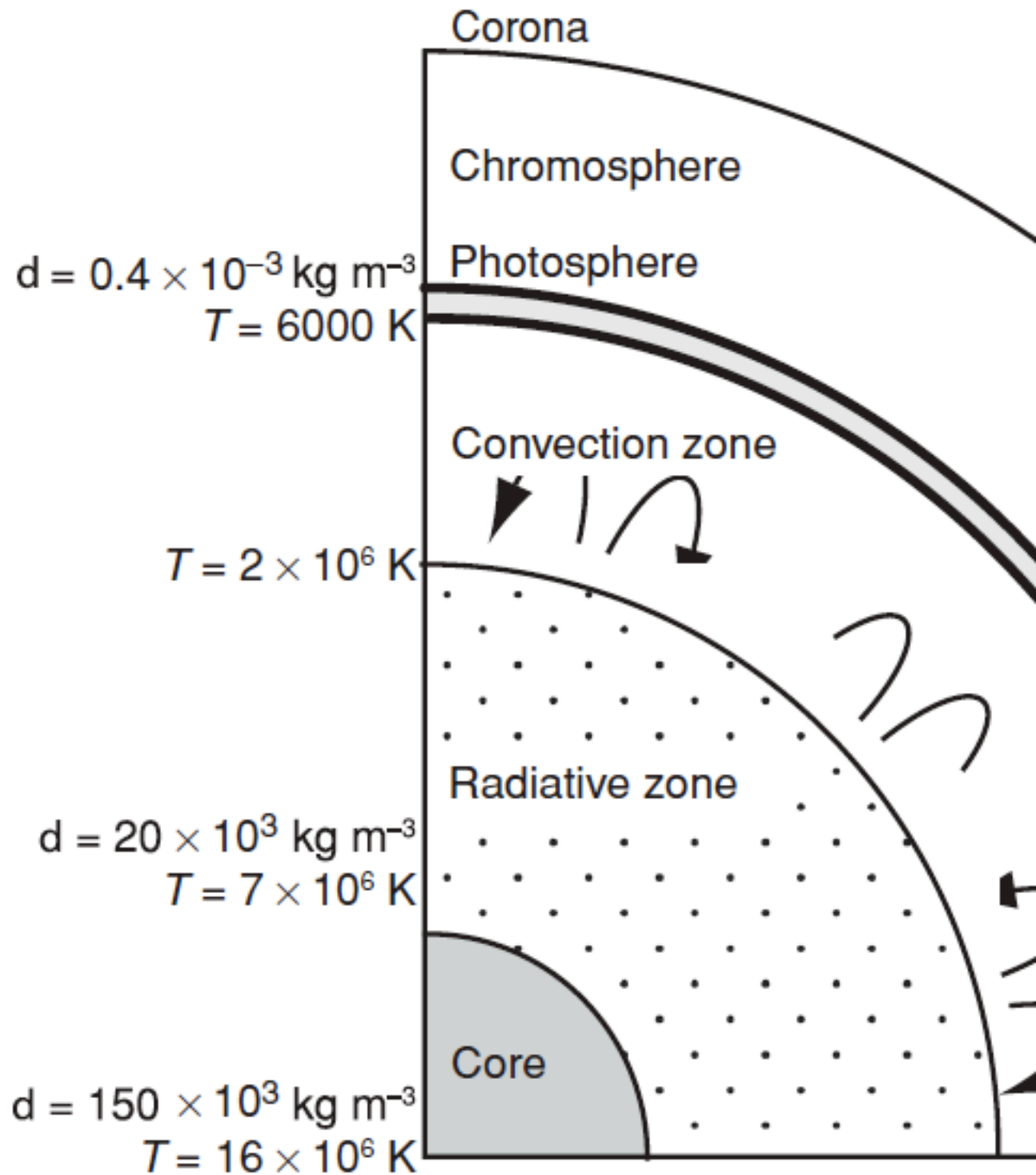


Figure 15.25

The solar wind, which is deflected by the Earth's magnetic field.

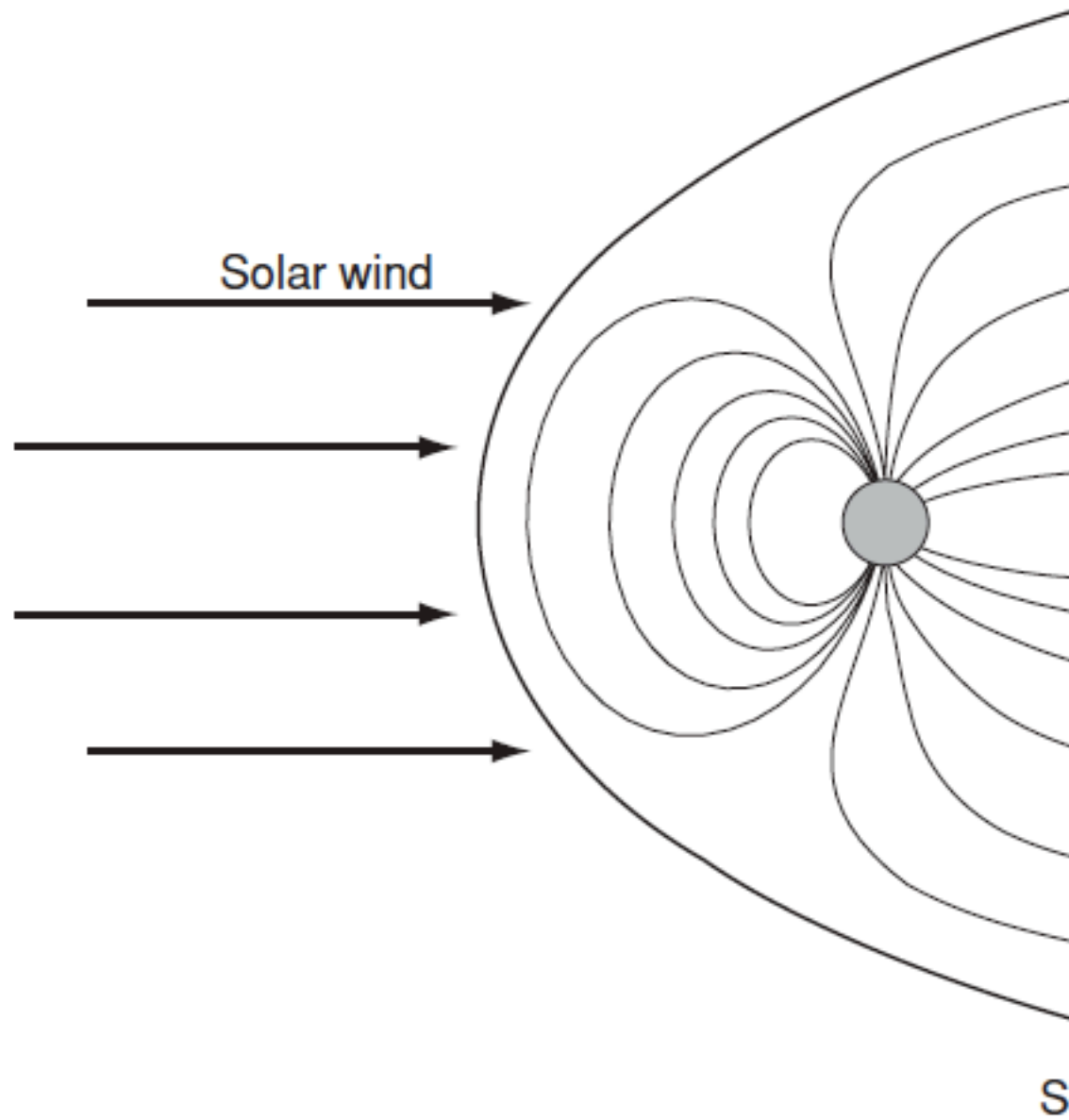
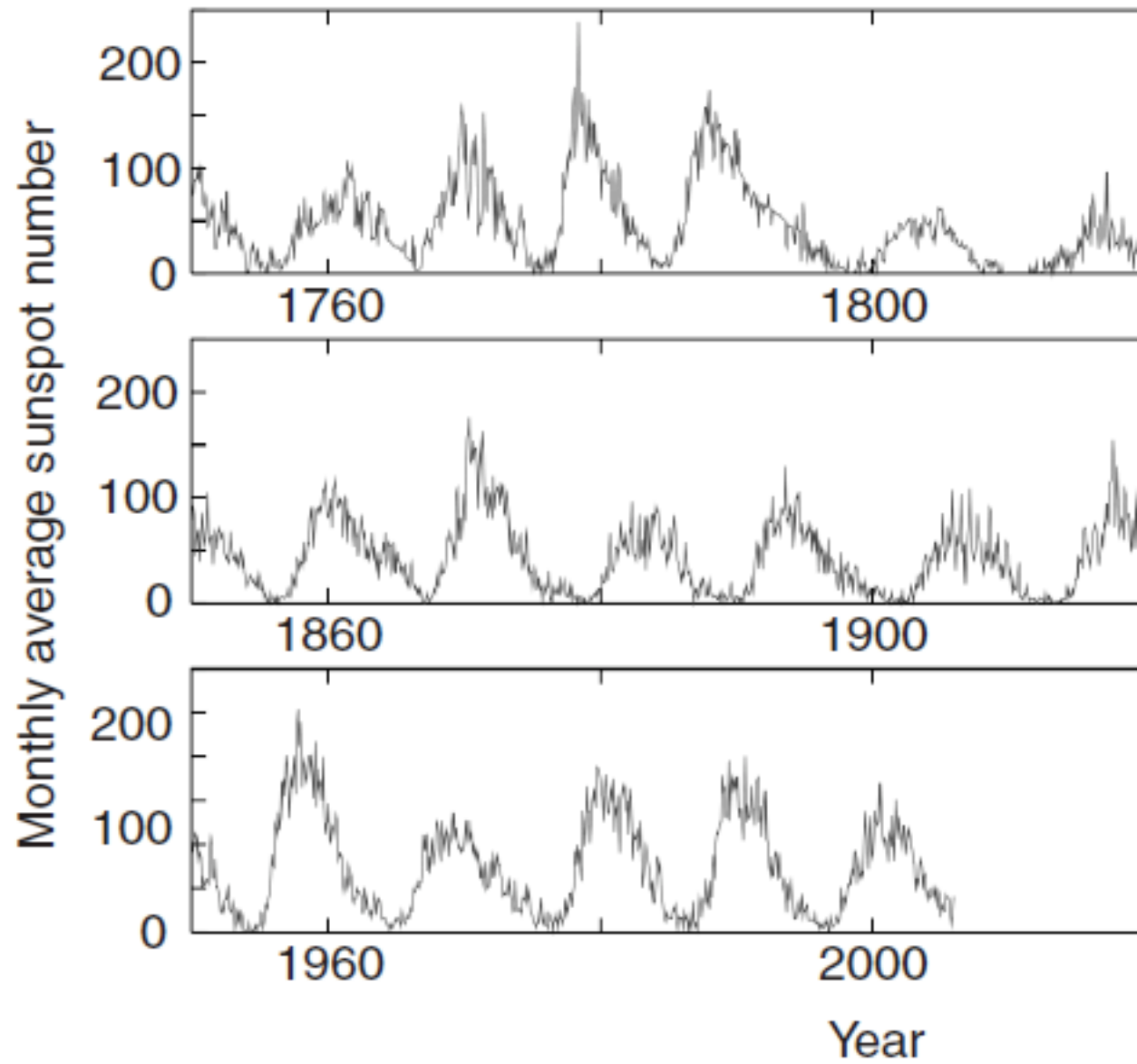




Figure 15.26

The 11-year sunspot cycle from 1760-2000.



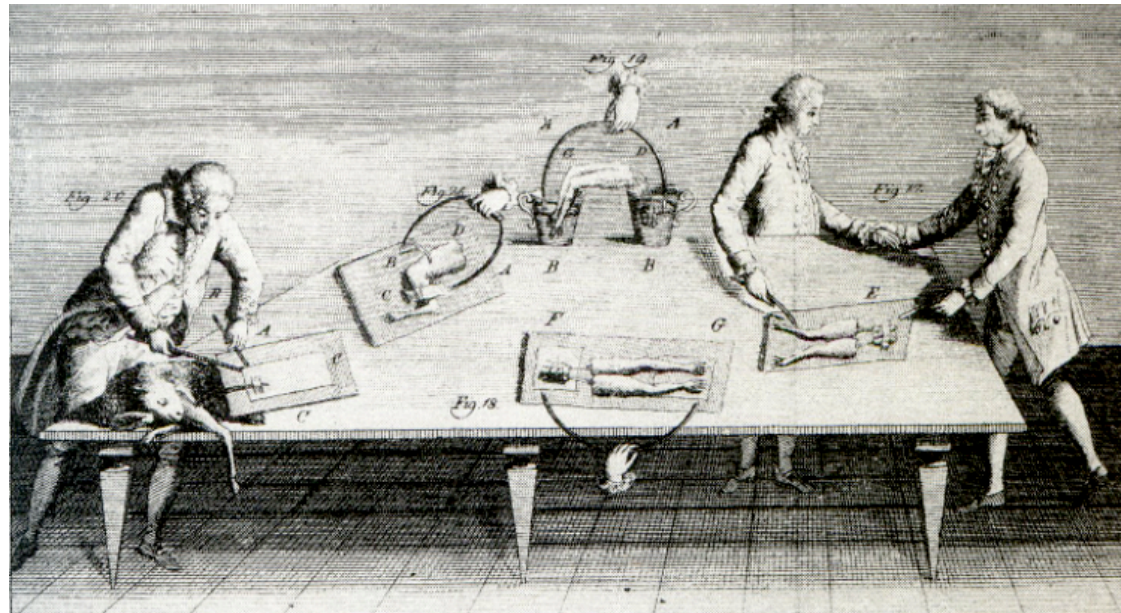
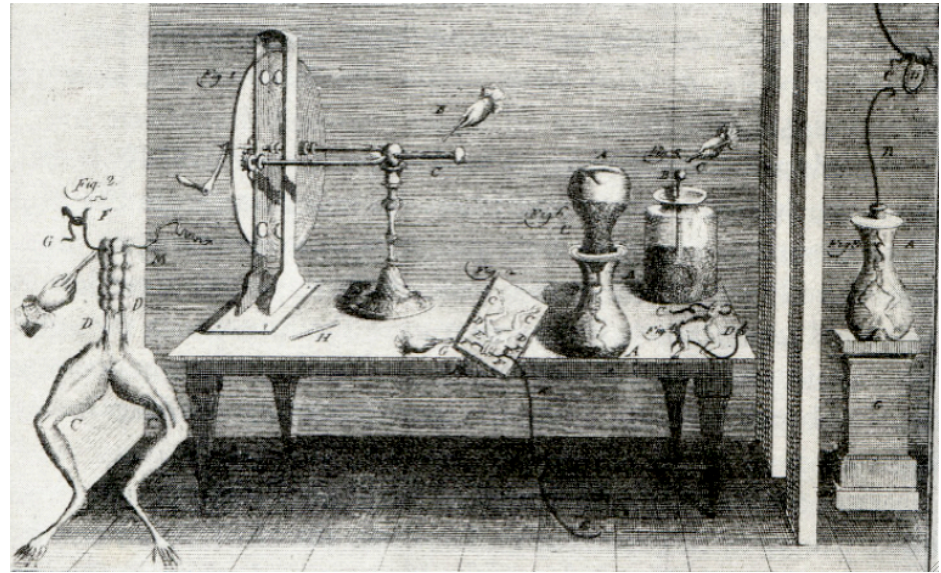
$$\mathcal{R}_m = v l \sigma \mu$$



A flux tube which gas been pushed out through the surface of the Sun, forming two sunspots.



The second half of the 18th century saw an upsurge of interest in electrical phenomena, and a quest for a connection between electricity and magnetism



Luigi Galvani studies animal electricity, in experiments on frogs legs and corpses – animal electricity



Anton Mesmer, a Viennese doctor enjoyed great success in his prerevolutionary Paris salon where he practiced cures with animal magnetism, around a bac.



RAPPORT  
DES COMMISSAIRES  
CHARGÉS PAR LE ROI,  
DE L'EXAMEN  
DU  
MAGNÉTISME ANIMAL.

Imprimé par ordre du Roi.



A PARIS,  
DE L'IMPRIMERIE ROYALE.

M. DCCLXXXIV.

The report which examined and dismissed animal magnetism was a landmark in the progress of science

