How the Heavens Go

Prof. David Kaiser

Monday, November 15, 2010, STS.003

Heavens unit

Overarching questions:

Are representations of astronomical phenomena *true* or merely *useful*?

How does scientific knowledge travel?

I. Galileo and the Inquisition

II. Newton and the Designer

III. Laplace and the Philosophes

Readings: Newton, *Letters to Richard Bentley*, 330 - 339;
Kragh, *Conceptions of Cosmos*, 67 – 89.

Galileo's Path

Galileo Galilei (1564 – 1642) was born into court culture: his father was a court musician at the Tuscan court in Florence. Galileo wanted to be a monk; his father wanted him to be a physician.

Ottavio Leoni, *Galileo*, 1624

They reached a compromise: Galileo studied mathematics at the University of Pisa.

Clever Appropriation

Galileo taught mathematics at the University of Pisa and the University of Padua during the 1580s and 1590s. He also served as a consultant to the Venetian Senate.

Photos of Galileo's telescope and "Life of Galileo," Bertolt Brecht, removed due to copyright restrictions.

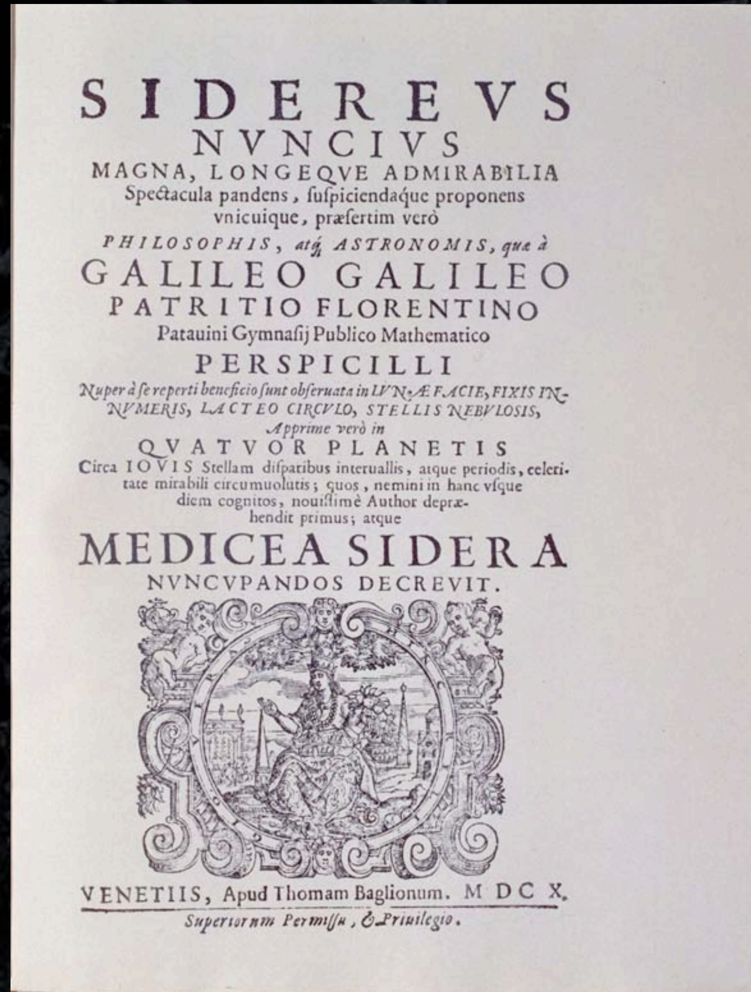
In 1609 he saw a spyglass, which had just been invented in the Netherlands. He made a few minor improvements and presented it to the Venetian Senate, as if it were entirely his own design.

They rewarded him with an improved salary in exchange for “his” invention.

Turning Skyward

Soon after impressing the Venetian Senate with the new telescope, Galileo turned it skyward. He quickly made three major discoveries:

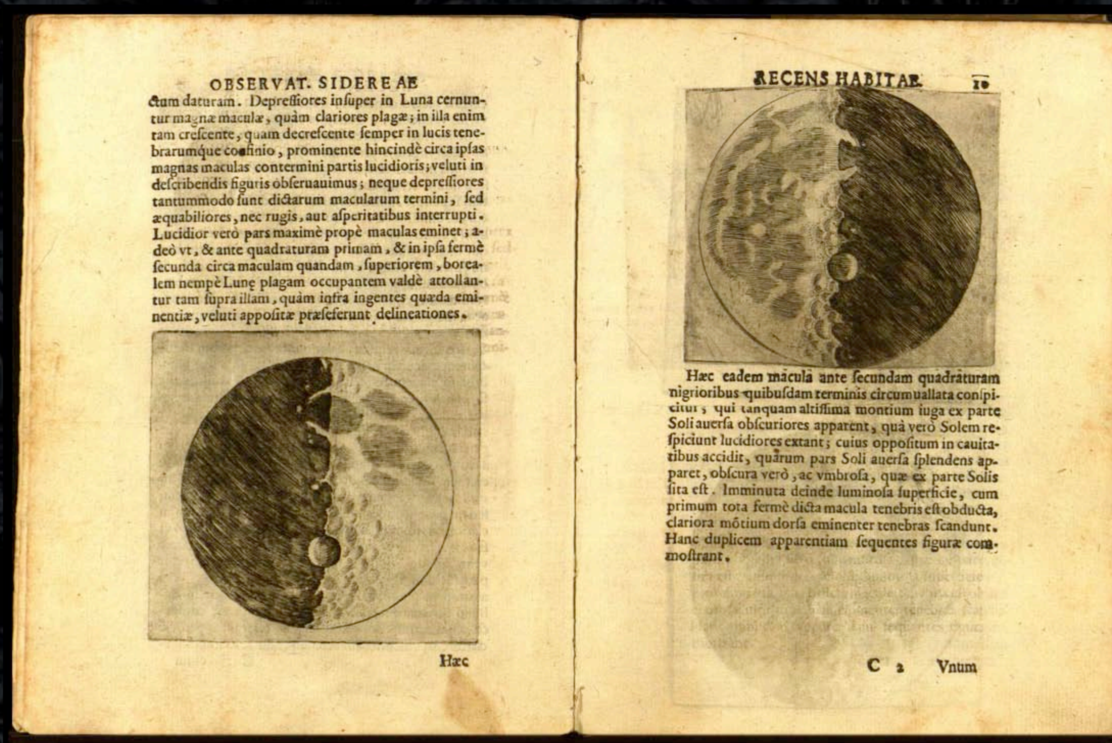
craters on the moon;
resolved the Milky Way into individual stars;
four moons circling Jupiter.


SIDEREVS
NVNCIVS
MAGNA, LONGEQVE ADMIRABILIA
Spectacula pandens, suspiciendaque proponens
vnicuique, præsertim verò
PHILOSOPHIS, atq; ASTRONOMIS, quæ à
GALILEO GALILEO
PATRITIO FLORENTINO
Patauini Gymnasij Publico Mathematico
PERSPICILLI
Nuper à se reperti beneficio sunt obseruata in LVNÆ FACIE, FIXIS IN-
NVMERIS, LACTEO CIRCVLO, STELLIS NEBVLOSIS,
Apprime verò in
QVATVOR PLANETIS
Circa IOVIS Stellam disparibus interuallis, atque periodis, celeri-
tate mirabili circumuolutis; quos, nemini in hanc vsque
diem cognitos, nouissimè Author depræ-
hendit primus; atque
MEDICEA SIDERA
NVNCVPANDOS DECREVIT.
VENETIIS, Apud Thomam Baglionum. M DC X.
Superiorum Permissu, & Priuilegio.

He quickly wrote up his findings in a tiny book, *Sidereus Nuncius*, or *Starry Messenger* (1610).

Moon’s Surface

Galileo had studied technical drawing, or *disegno*, as a student. He was adept at using shadowing and perspective to represent 3D structures. He thus painted the moon’s surface to accentuate its Earth-like features: mountains and valleys.


OBSERVAT. SIDEREAE

ctum daturam. Depreſſiores inſuper in Luna cernuntur magnæ maculæ, quàm clariores plagæ; in illa enim tam creſcente, quam decreſcente ſemper in lucis tenebrarumque confinio, prominente hincindè circa ipſas magnas maculas contermini partis lucidioris; veluti in deſcribendis figuris obſeruauimus; neque depreſſiores tantummodo ſunt dictarum macularum termini, ſed æquabiliores, nec rugis, aut aſperitatibus interrupti. Lucidior verò pars maximè propè maculas eminet; adeò vt, & ante quadraturam primam, & in ipſa fermè ſecunda circa maculam quandam, ſuperiorem, borealem nempè Lunę plagam occupantem valdè attollantur tam ſupra illam, quàm infra ingentes quæda eminentiæ, veluti appoſitæ præſeferunt delineationes.

Hæc

RECENS HABITAE 10

Hæc eadem macula ante ſecundam quadraturam nigrioribus quibuſdam terminis circumuallata conſpicitur; qui tanquam altiſſima montium iuga ex parte Soli auerſa obſcuriores apparent, quà verò Solem reſpiciunt lucidiores extant; cuius oppoſitum in cauitatibus accidit, quarum pars Soli auerſa ſplendens apparet, obſcura verò, ac vmbroſa, quæ ex parte Solis ſita eſt. Imminuta deinde luminoſa ſuperficie, cum primum tota fermè dicta macula tenebris eſt obducta, clariora mōtium dorſa eminenter tenebras ſcandunt. Hanc duplicem apparentiam ſequentes figuræ commoſtrant.

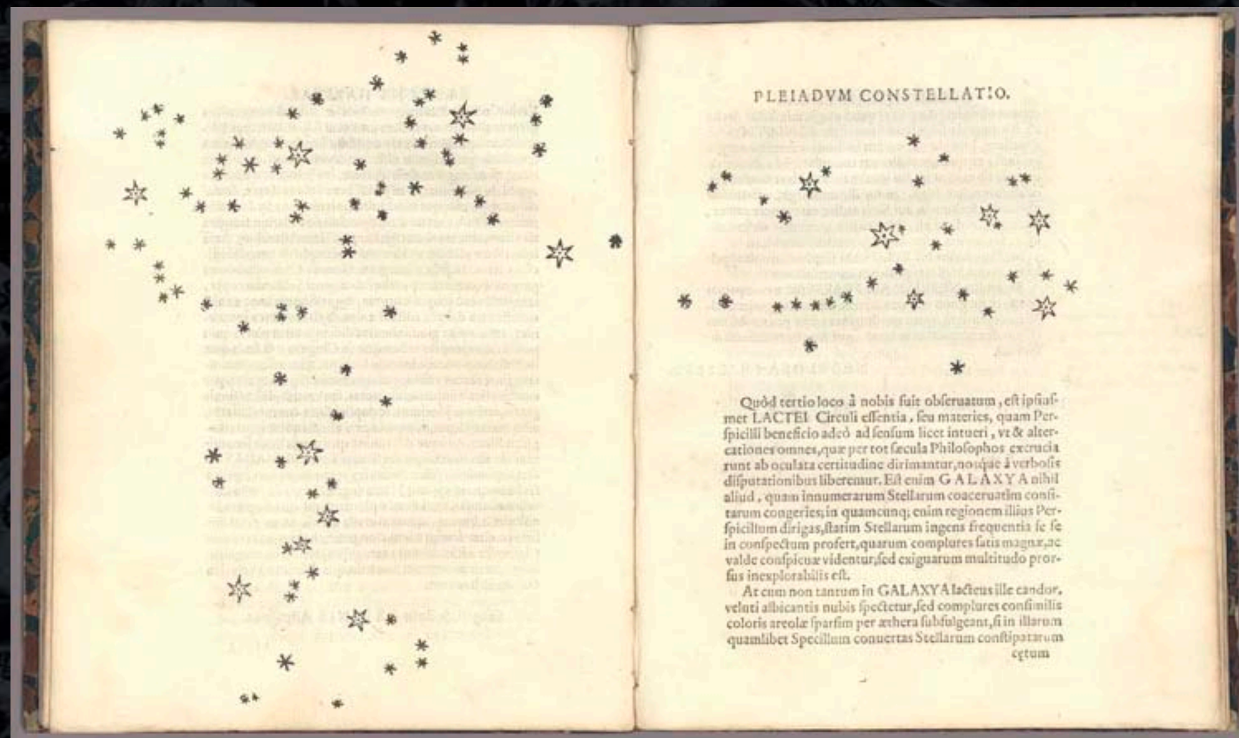
C 2 Vnum

Galileo, *Sidereus Nuncius*,1610

If the moon had craggy features like the Earth, perhaps it was not made of Aristotelian quintessence after all.

"It's Full of Stars…"

Galileo was also the first to resolve the Milky Way into discrete stars, instead of an indiscriminate band of light.

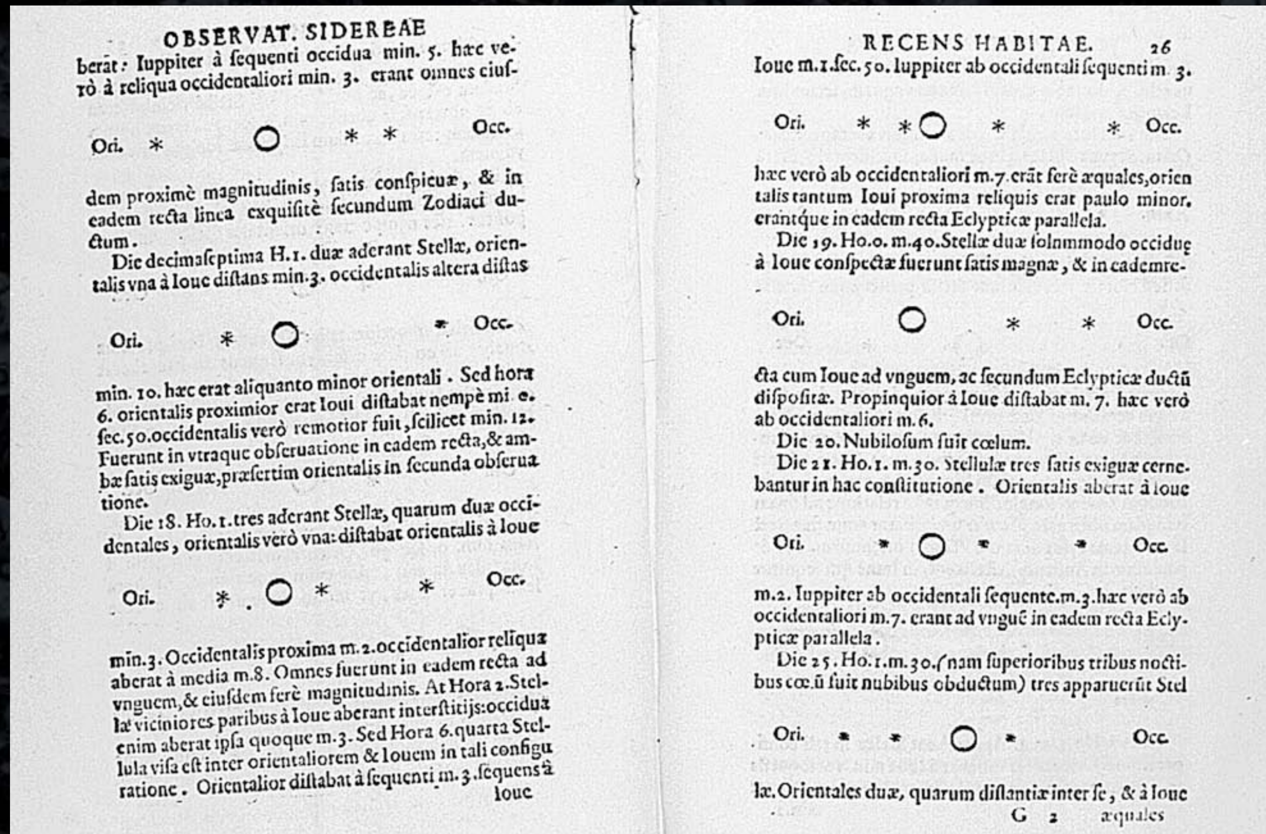


Galileo, *Sidereus Nuncius*, 1610

Galileo thus first suggested that the Milky Way was just like other known celestial objects, like the constellations.

Biggest Find of All

Most important – at least for Galileo's subsequent career – was his discovery of 4 moons orbiting Jupiter.



OBSERVAT. SIDEREAE

berāt: Iuppiter à ſequenti occidua min. 5. hæc ve-
rò à reliqua occidentaliori min. 3. erant omnes eiuſ-

Ori. Occ.

dem proximè magnitudinis, ſatis conſpicuæ, & in
eadem recta linea exquiſitè ſecundum Zodiaci du-
ctum.

Die decimaſeptima H. 1. duæ aderant Stellæ, orien-
talis vna à Ioue diſtans min. 3. occidentalis altera diſtas

Ori. Occ.

min. 10. hæc erat aliquanto minor orientali. Sed hora
6. orientalis proximior erat Ioui diſtabat nempè mi. e.
ſec. 50. occidentalis verò remotior fuit, ſcilicet min. 12.
Fuerunt in vtraque obſeruatione in eadem recta, & am-
bæ ſatis exiguæ, præſertim orientalis in ſecunda obſerua
tione.

Die 18. Ho. 1. tres aderant Stellæ, quarum duæ occi-
dentales, orientalis verò vna: diſtabat orientalis à Ioue

Ori. Occ.

min. 3. Occidentalis proxima m. 2. occidentalior reliqua
aberat à media m. 8. Omnes fuerunt in eadem recta ad
vnguem, & eiuſdem ferè magnitudinis. At Hora 2. Stel-
læ viciniores paribus à Ioue aberant interſtitijs: occidua
enim aberat ipſa quoque m. 3. Sed Hora 6. quarta Stel-
lula viſa eſt inter orientaliorem & Iouem in tali configu
ratione. Orientalior diſtabat à ſequenti m. 3. ſequens à
Ioue

RECENS HABITAE. 26

Ioue m. 1. ſec. 50. Iuppiter ab occidentali ſequenti m. 3.

Ori. Occ.

hæc verò ab occidentaliori m. 7. erāt ferè æquales, orien
talis tantum Ioui proxima reliquis erat paulo minor.
erantque in eadem recta Eclypticæ parallela.

Die 19. Ho. 0. m. 40. Stellæ duæ ſolummodo occiduę
à Ioue conſpectæ fuerunt ſatis magnæ, & in eadem re-

Ori. Occ.

cta cum Ioue ad vnguem, ac ſecundum Eclypticæ ductū
diſpoſitæ. Propinquior à Ioue diſtabat m. 7. hæc verò
ab occidentaliori m. 6.

Die 20. Nubiloſum fuit cœlum.

Die 21. Ho. 1. m. 30. Stellulæ tres ſatis exiguæ cerne-
bantur in hac conſtitutione. Orientalis aberat à Ioue

Ori. Occ.

m. 2. Iuppiter ab occidentali ſequente. m. 3. hæc verò ab
occidentaliori m. 7. erant ad vnguē in eadem recta Ecly-
pticæ parallela.

Die 25. Ho. 1. m. 30. (nam ſuperioribus tribus nocti-
bus cœlū fuit nubibus obductum) tres apparuerūt Stel

Ori. Occ.

læ. Orientales duæ, quarum diſtantiæ inter ſe, & à Ioue
G 2 æquales

Galileo saw in the moons an important Copernican message: if both the Earth and Jupiter could have their own moons, maybe the Earth was also "just" a planet – not the special center of the universe.

"Medicean Stars"

Jupiter's moons became Galileo's ticket. These were among the first new objects in the sky for millennia – so he had "naming rights." He chose to call them the "Medicean Stars," in honor of Cosimo II de Medici, Grand Duke of Tuscany.

Michele Castrucci, *Cosimo II de Medici*, ca. 1610

Image of "Galileo's Courtier: The Practice of Science in the Culture of Absolutism," Mario Biagioli, removed due to copyright restrictions.

Cosimo's symbol (in family iconography, coat of arms, etc.) was Jupiter; and "Cosimo" was already close to "cosmos." Now Galileo could show that Cosimo/Jupiter had his own band of loyal followers who never strayed far from their leader.

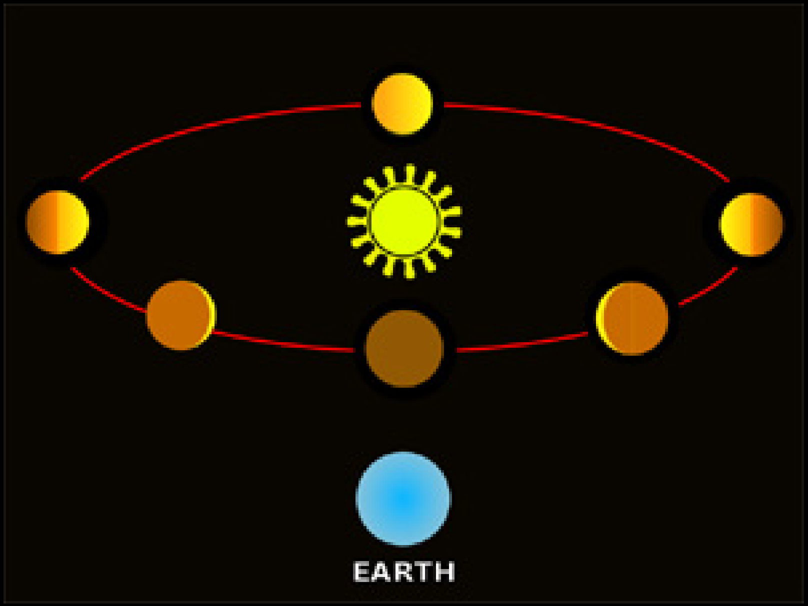
Court Philosopher

In the *Sidereus Nuncius*, Galileo made passing remarks about Copernicanism. Once he got to Florence, however, he became Cosimo's *Court Philosopher*, rather than a university mathematician. Now it was his *job* to talk about causes – not just useful calculations but physical truths of astronomy.

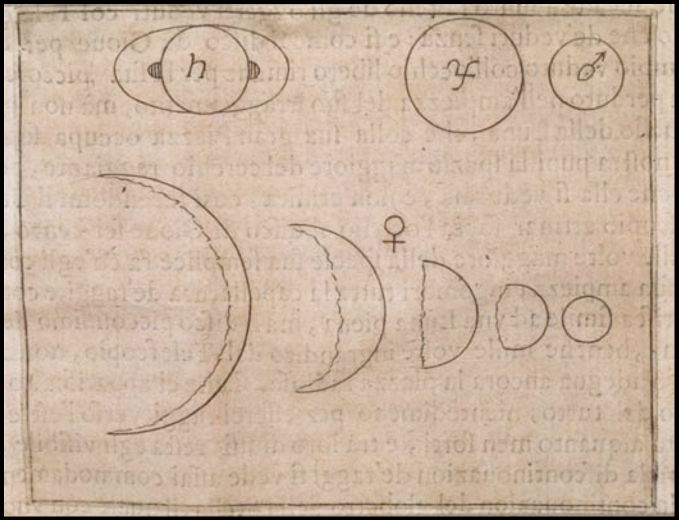
Photo of the De Medici's Boboli Gardens in Florence removed due to copyright restrictions.

His position at court also likely shaped his choice of literary conventions. His later books were published as *dialogues*: part of his job was to entertain the Grand Duke with after-dinner repartee.

Galileo's Copernicanism



Phases of Venus. This image is public domain.



Galileo, *Il Saggiatore*, 1623

"Horns" [Phases] of Venus: Galileo reasoned that Venus should exhibit the full range of phases – just like the moon – if it truly orbited the sun and not the earth. He observed the waxing and waning through his telecope.

Galileo failed to mention that the same effect would occur in the Tychonic system.

Letter to Christina

Emboldened by his new position, Galileo wrote an “open letter” to Cosimo’s mother, the Grand Duchess Christina, in 1615. She had asked Galileo how one might reconcile Copernicanism with Scripture.

He used the “open letter” format to avoid having to go through the official Church censors.

Grand Duchess Christina (1565 – 1637)

Galileo cautioned against literal interpretations of the Bible. The Bible teaches us “how to go to Heaven, not how the heavens go.”

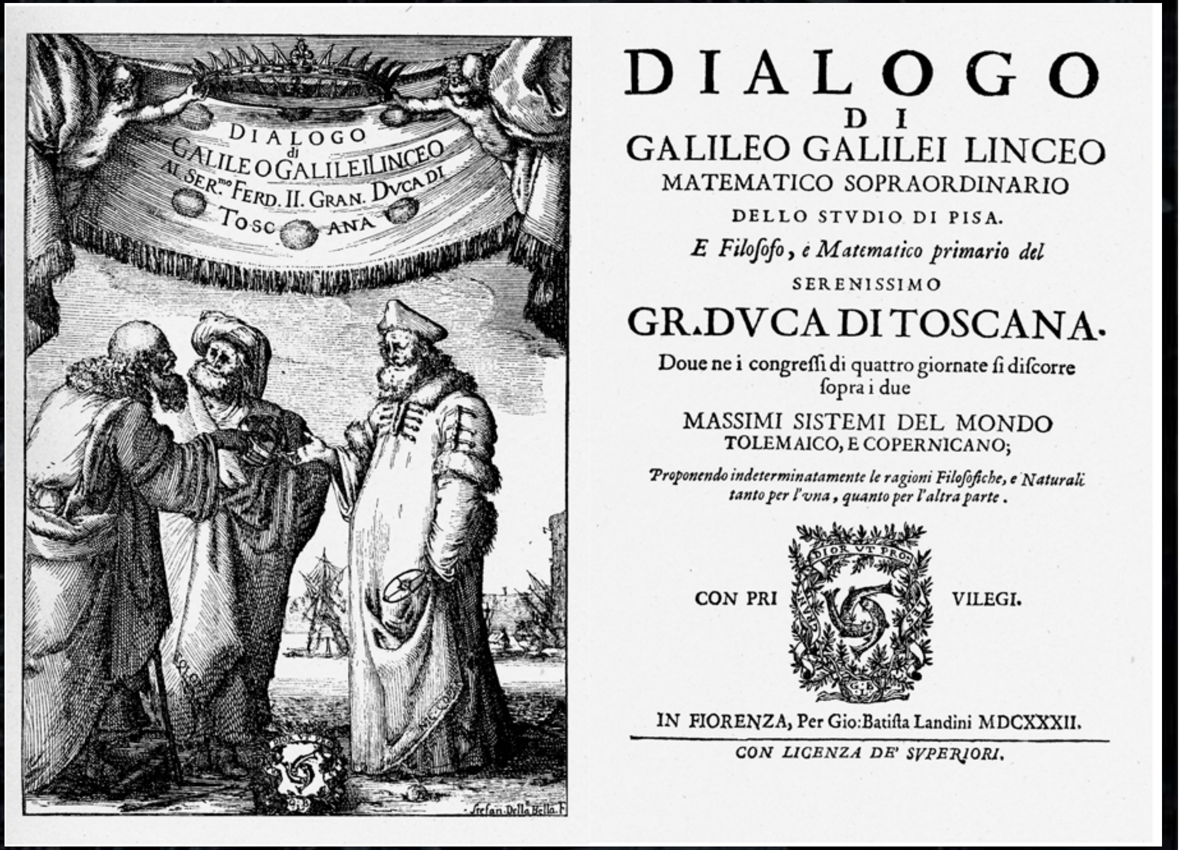
Reaction in Rome

Galileo's rivals sent copies to the Vatican. Cardinal Roberto Bellarmine responded by placing Copernicus's *De Revolutionibus* on the Index in 1616: the book could not be re-published until the nature of heliocentrism was made more clearly *hypothetical.*

Bellarmine delivered the verdict to Galileo in person: he was to stop defending Copernicanism.

New Pope, New Hope

Bellarmine died in 1624, and Cardinal Barberini became Pope Urban soon after that. Barberini had a more liberal reputation; he allowed Galileo to discuss Copernicanism, so long as it was properly hypothetical.



Galileo took this as license to publish his *Dialogues on the Two Chief World Systems* (1632).

Trial!

Two main interpretations of Galileo's trial by the Inquisition of 1632:

1. Galileo was rational; the Church was backward or stubborn.

Cristiano Banti, *Galileo Facing the Roman Inquisition*, 1857

2. The Church was reasonable; Galileo was stubborn. He repeatedly overstepped his bounds (lecturing Cardinals how to interpret the Bible; placing the Pope's positions in mouth of *Simplicius*); he overclaimed what he could prove; he left out the Church's preferred system (Tychonic) altogether; and he misunderstood the nature of scientific theories, which are always subject to revision.

House Arrest

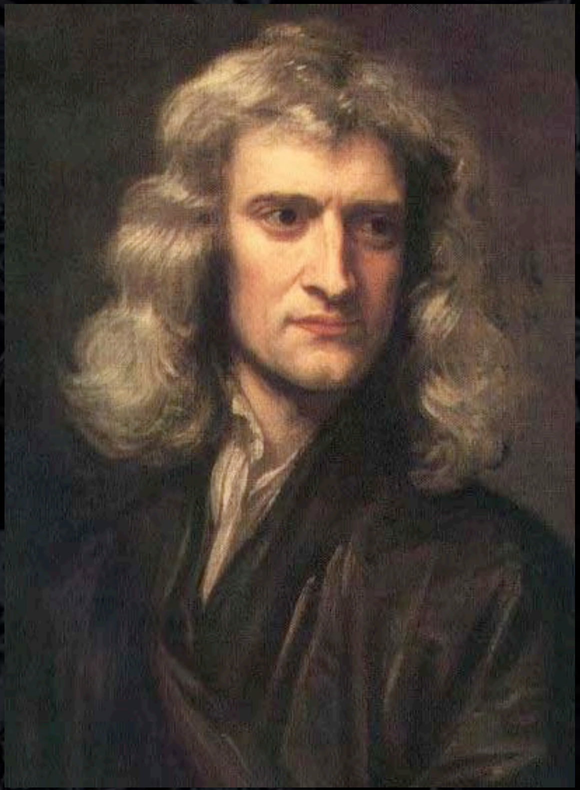
Galileo was forced to recant ("Eppur si muove") and sentenced to house arrest. His daughter – a nun – said all of his penitence prayers on his behalf.

Image of "Galileo's Daughter: A Historical Memoir of Science, Faith, and Love," by Dava Sobel, removed due to copyright restrictions.

While under house arrest, he wrote his *Discourses on Two New Sciences*, and had it smuggled out for publication in the Netherlands.

"Let Newton Be…"

Isaac Newton (1642 – 1727) introduced *universal gravitation* in his *Principia* (1687), alongside his three laws of motion.

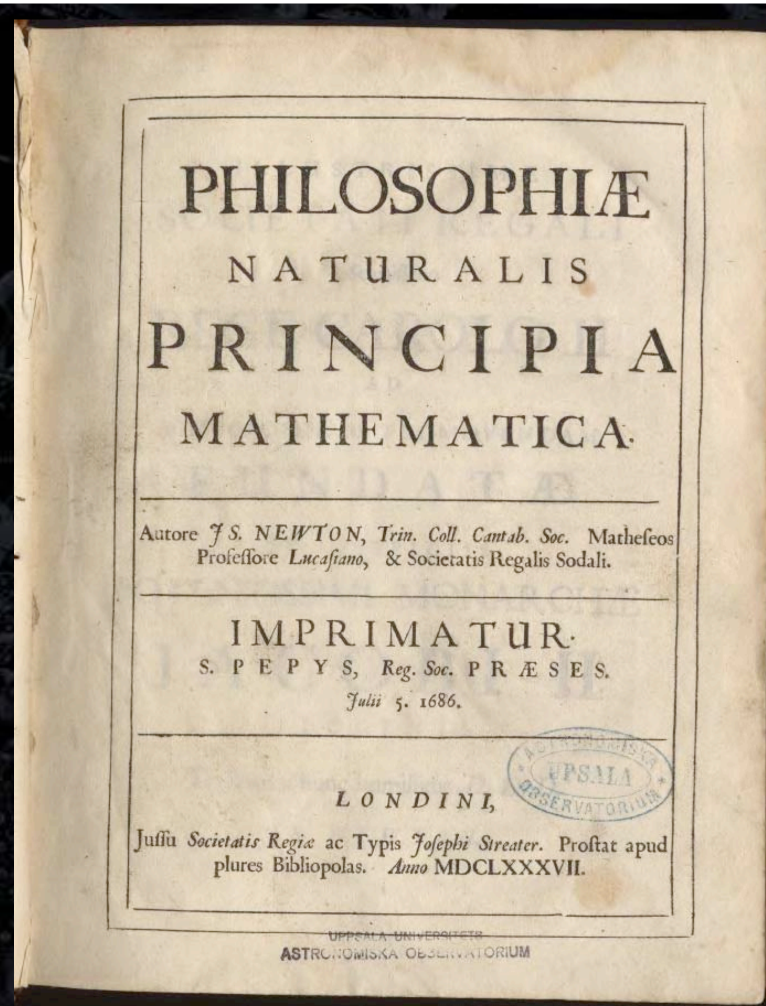


Godfrey Kneller, portrait of Isaac Newton, 1689

> "Nature and nature's laws lay hid in night.
> God said, 'Let Newton be!,' and all was light."
>
> Alexander Pope (1688 – 1744)

Inverse-Square Law

Newton began with Kepler's third law (R^3 / T^2 = constant), assuming *circular* orbits. The latest data from the Astronomer Royal, John Flamsteed, showed that most planetary orbits were indistinguishable from circles.


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.

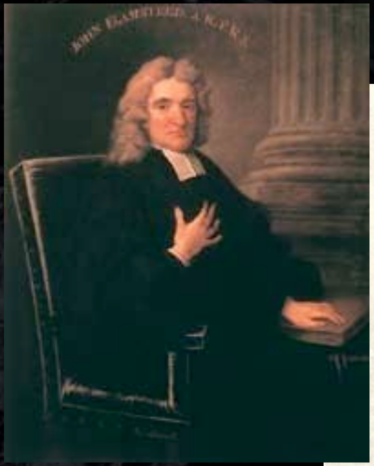
Newton had already derived $a = v^2 / r$ for circular motion. To obey Kepler's law, the force of gravity between the sun and planet must then vary as $1/r^2$.

From his own third law of motion, Newton then deduced that $F = Gm_1 m_2 / r^2$.

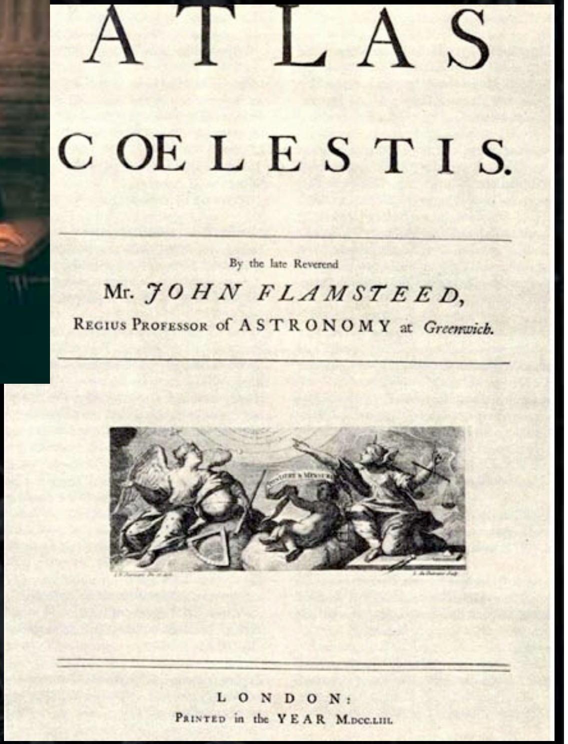
Where's That Data?

Flamsteed on Halley, ca. 1686: his most remarkable quality was "his art of filching from other people, and making their works is own."

Flamsteed showed Newton much of his data on the Moon, subject to Newton's promise not to share them...



John Flamsteed, by Thomas Gibson, 1712



ATLAS
COELESTIS.

By the late Reverend
Mr. JOHN FLAMSTEED,
Regius Professor of ASTRONOMY at Greenwich.

LONDON:
Printed in the YEAR M.DCC.LIII.

Image of "The Nature of the Book: Print and Knowledge in the Making," Adrian Johns, removed due to copyright restrictions.

Flamsteed: "I complained then of my Catalogue being printed without my knowledge, & that I was Robd of the fruits of my Labours."

"System of the World"

Image courtesy of fragglexarmy on Flickr.

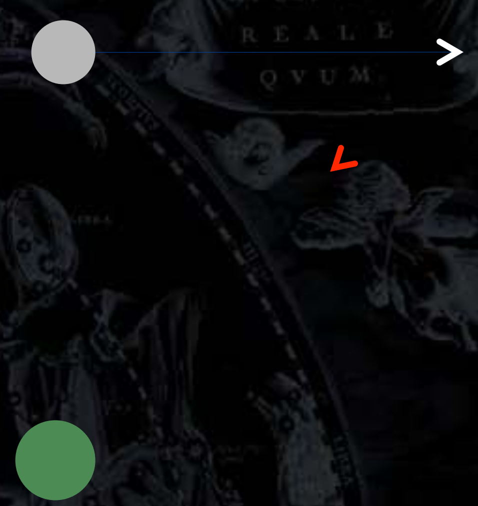
Image courtesy of NASA Solar System Exploration on Flickr.

Newton demonstrated that universal gravitation could account for both objects' motion.

Things Fall Down

$$m_a\, a_{\text{apple}} = G m_a M_E / R_E^2$$

$$m_M\, a_{\text{moon}} = G m_M M_E / R_M^2$$



a_{apple} = 32 ft / sec^2, and
$d = (1/2)\ a\ t^2$. In one second,
the apple will fall 16 feet.

$R_M = 60\ R_E$, so $a_{\text{moon}} = a_{\text{apple}}/3600$.
In one second, the Moon should
fall 16 ft/3600 = 0.053 inches.

The motion caused by gravitation exactly matched the amount by which the moon must fall each second in order to remain on its orbital path.

Biblical Preoccupations

Newton spent even more time scrutinizing Biblical passages than he spent on natural philosophy. Like a true Renaissance Humanist, Newton was convinced that the true meaning of the Scriptures had been obscured by centuries of shoddy translations.

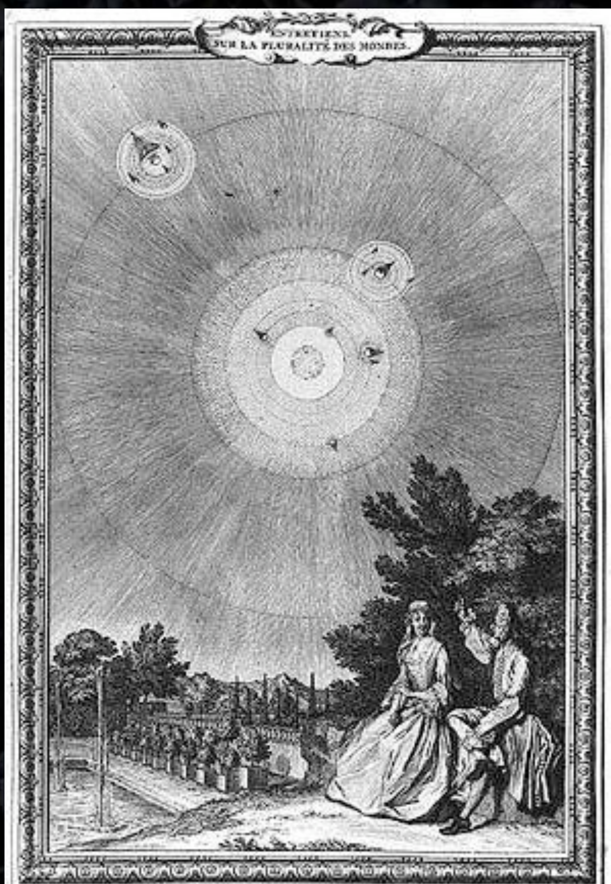
Newton's tomb, Westminster Abbey

Photo courtesy of Dean Jackson on Flickr.

Based on his intensive study, Newton secretly broke from Anglicanism. He was devout but anti-Trinitarian.

Wisdom of Design

Newton believed the cosmos displayed clear evidence of a "Master Architect," or of intelligent design. If the Earth's distance from the sun had been slightly different, the planet would not be habitable by life as we know it.



Bernard de Fontenelle, *Conversations on the Plurality of Worlds* (1686)

Richard Bentley (1662 – 1742)

Newton's position, as articulated in letters to the theologian Richard Bentley, 1690s, helped launch "natural theology."

Beyond a Watchmaker

Newton saw evidence of God's hand in more than just setting up the universe. Newton studied *perturbations* to the planets' orbits, and became convinced that instabilities would *accumulate* over time.

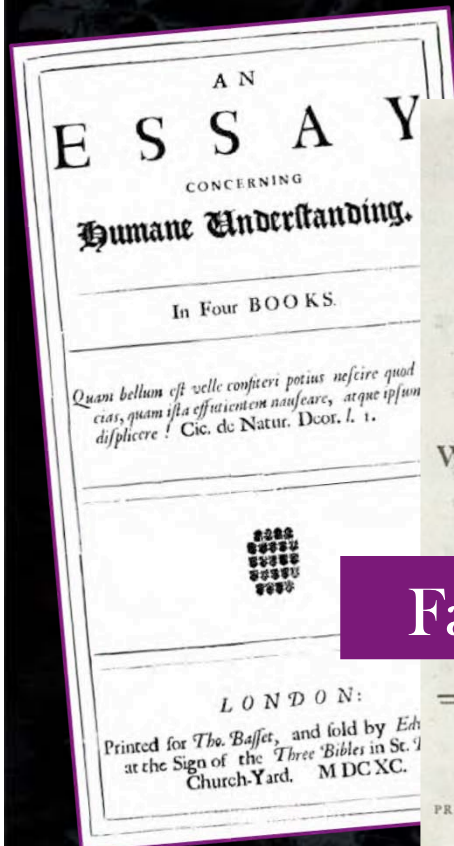
Images of Jupiter and Saturn, and a grandfather clock, removed due to copyright restrictions.

Jupiter and Saturn perturb each other's orbits; Newton feared that these perturbations would grow without bound.

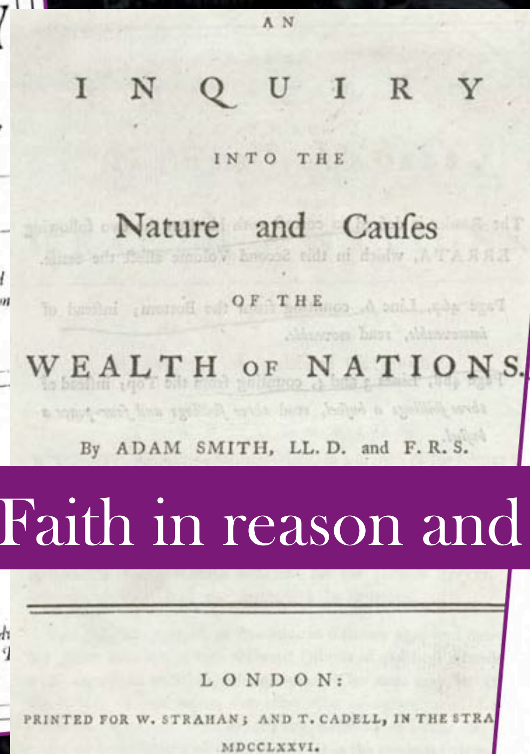
So Newton concluded that God must *constantly intervene* in the universe, to keep the whole system stable.

Age of Enlightenment

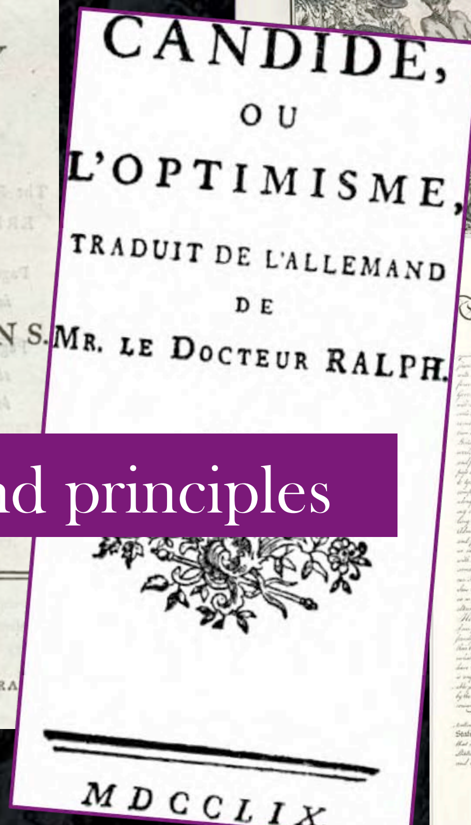
Inspired by natural philosophy



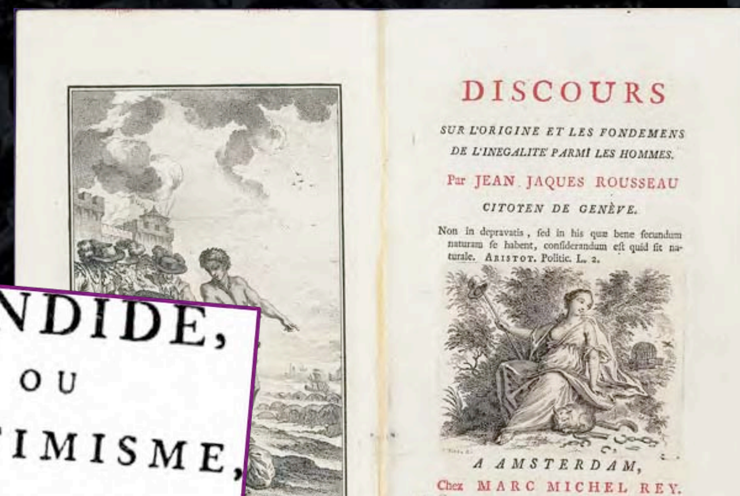
AN
ESSAY
CONCERNING
Humane Understanding.
In Four BOOKS.
Quam bellum est velle confiteri potius nescire quod nescias, quam ista effutientem nauseare, atque ipsum sibi displicere! Cic. de Natur. Deor. *l.* 1.
LONDON:
Printed for *Tho. Basset*, and sold by *Edw.* ...
at the Sign of the *Three Bibles* in St. ...
Church-Yard. MDCXC.



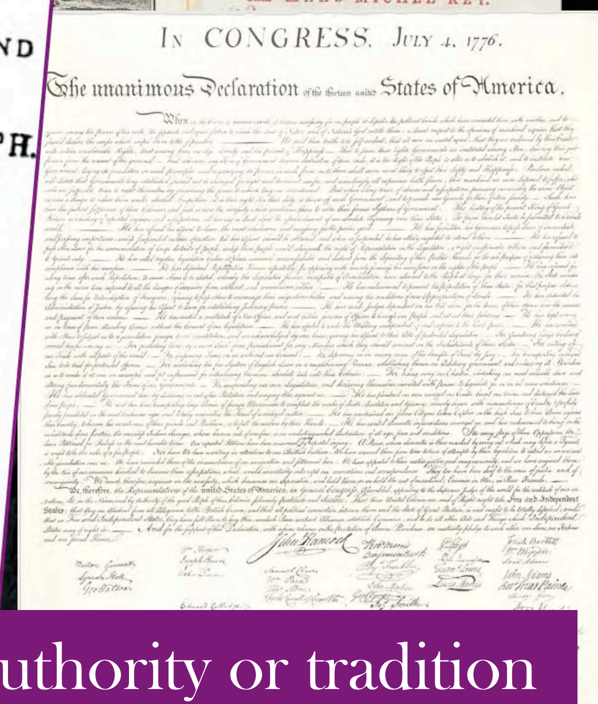
AN
INQUIRY
INTO THE
Nature and Causes
OF THE
WEALTH OF NATIONS.
By ADAM SMITH, LL.D. and F.R.S.
LONDON:
PRINTED FOR W. STRAHAN; AND T. CADELL, IN THE STRA...
MDCCLXXVI.



CANDIDE,
OU
L'OPTIMISME,
TRADUIT DE L'ALLEMAND
DE
MR. LE DOCTEUR RALPH.
MDCCLIX.



DISCOURS
SUR L'ORIGINE ET LES FONDEMENS
DE L'INEGALITÉ PARMI LES HOMMES.
Par JEAN JAQUES ROUSSEAU
CITOYEN DE GENÈVE.
Non in depravatis, sed in his quæ bene secundum naturam se habent, considerandum est quid sit naturale. ARISTOT. Politic. L. 2.
A AMSTERDAM,
Chez MARC MICHEL REY.



IN CONGRESS. JULY 4, 1776.
The unanimous Declaration of the thirteen united States of America.

Faith in reason and principles

Suspicion of authority or tradition

Enter Laplace

Pierre Simon de Laplace (1749 – 1827) grew up studying "natural theology" arguments inspired by Newton. But by the time of his childhood — even before the French Revolution — such arguments held much less sway, even among theology students like the young Laplace.

Mme. Feytaud, *Pierre Simon de Laplace*, 1842

After studying theology, Laplace moved to Paris and studied under Jean d'Alembert, famous *philosophe* and co-editor of the *Encyclopédie*. D'Alembert recommended Laplace for a mathematics professorship.

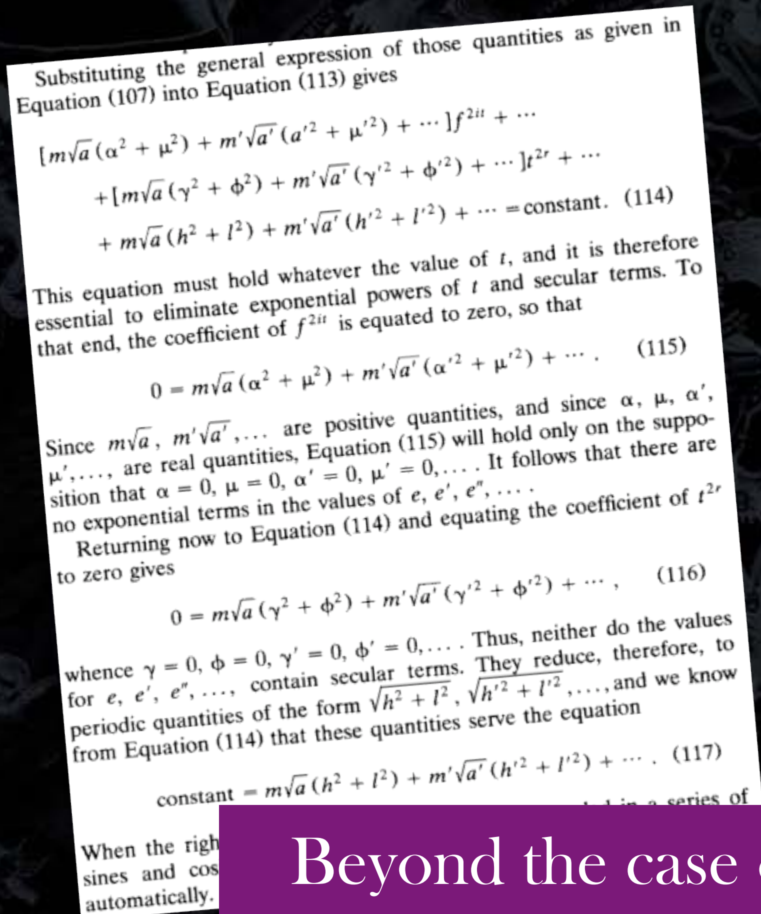
Jupiter and Saturn Again

The latest observational data indicated that Jupiter was *accelerating* in its motion, while Saturn was *decelerating*.

Image of Jupiter and Saturn removed due to copyright restrictions.

In 1786, Laplace demonstrated in a calculational *tour de force* that the two effects balanced each other, and in fact they should reverse in roughly 900 years.

Searching for Stability



Substituting the general expression of those quantities as given in Equation (107) into Equation (113) gives

$$[m\sqrt{a}\,(\alpha^2+\mu^2)+m'\sqrt{a'}\,(\alpha'^2+\mu'^2)+\cdots]f^{2it}+\cdots$$
$$+[m\sqrt{a}\,(\gamma^2+\phi^2)+m'\sqrt{a'}\,(\gamma'^2+\phi'^2)+\cdots]t^{2r}+\cdots$$
$$+m\sqrt{a}\,(h^2+l^2)+m'\sqrt{a'}\,(h'^2+l'^2)+\cdots=\text{constant}. \quad (114)$$

This equation must hold whatever the value of t, and it is therefore essential to eliminate exponential powers of t and secular terms. To that end, the coefficient of f^{2it} is equated to zero, so that

$$0=m\sqrt{a}\,(\alpha^2+\mu^2)+m'\sqrt{a'}\,(\alpha'^2+\mu'^2)+\cdots. \quad (115)$$

Since $m\sqrt{a}$, $m'\sqrt{a'}$, ... are positive quantities, and since α, μ, α', μ', ..., are real quantities, Equation (115) will hold only on the supposition that $\alpha=0$, $\mu=0$, $\alpha'=0$, $\mu'=0$, ... It follows that there are no exponential terms in the values of $e, e', e'', \ldots$.

Returning now to Equation (114) and equating the coefficient of t^{2r} to zero gives

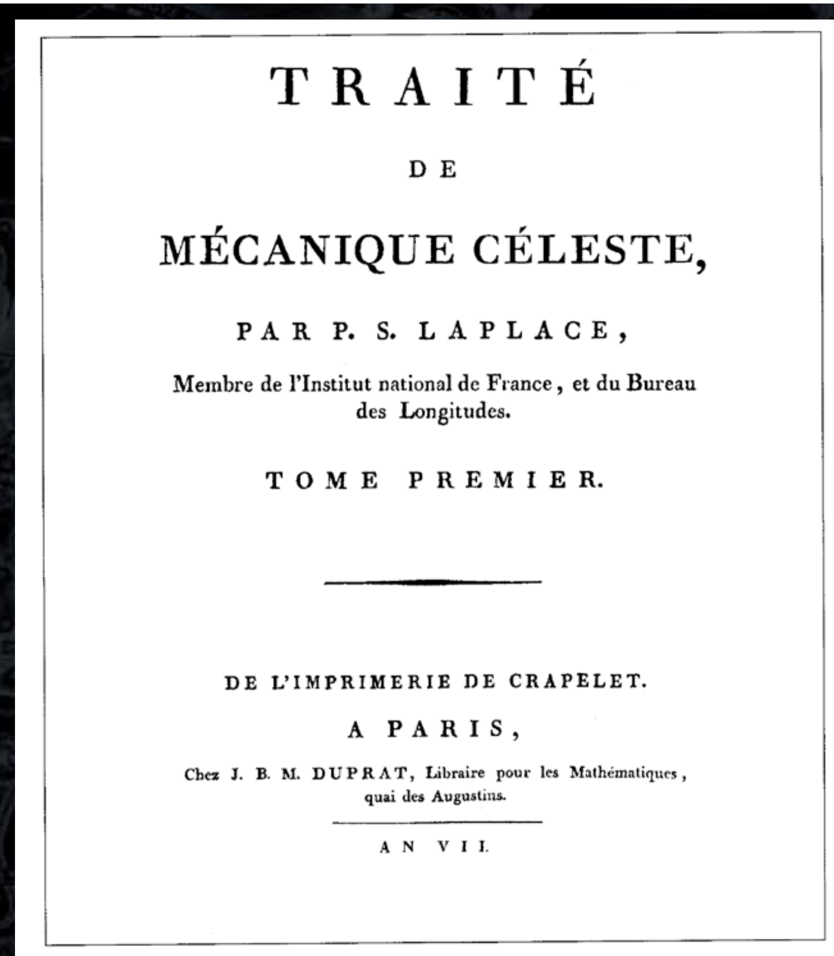
$$0=m\sqrt{a}\,(\gamma^2+\phi^2)+m'\sqrt{a'}\,(\gamma'^2+\phi'^2)+\cdots, \quad (116)$$

whence $\gamma=0$, $\phi=0$, $\gamma'=0$, $\phi'=0$, ... Thus, neither do the values for $e, e', e'', \ldots$, contain secular terms. They reduce, therefore, to periodic quantities of the form $\sqrt{h^2+l^2}$, $\sqrt{h'^2+l'^2}$, ..., and we know from Equation (114) that these quantities serve the equation

$$\text{constant}=m\sqrt{a}\,(h^2+l^2)+m'\sqrt{a'}\,(h'^2+l'^2)+\cdots. \quad (117)$$

... series of

When the righ
sines and cos
automatically.



TRAITÉ

DE

MÉCANIQUE CÉLESTE,

PAR P. S. LAPLACE,

Membre de l'Institut national de France, et du Bureau des Longitudes.

TOME PREMIER.

DE L'IMPRIMERIE DE CRAPELET.

A PARIS,

Chez J. B. M. DUPRAT, Libraire pour les Mathématiques, quai des Augustins.

AN VII.

Beyond the case of Jupiter and Saturn, Laplace demonstrated that such perturbations do not grow without bound; the solar system is *stable*. Newton's laws alone — with no divine intervention — could account for all observations.

Any Place for God?

In 1802, Laplace reported to Emperor Napoleon Bonaparte, “a chain of natural causes would account for the construction and preservation of the wonderful system of the world.”

Napoleon inquired: “Where is the place for God in your system?”

Jacques-Louis David, *The Emperor Napoleon*, 1812

Laplace: “I have no need for that hypothesis.”

Reading Meaning in the Heavens