The Starry Messenger

Instructors' Booklet

AN INTRODUCTION TO THE STARRY MESSENGER

Welcome to *The Grand Book*! All wisdom of men and immortals lie within its covers… but there's a *curse* on those who don't use it properly – so listen up!

Sidereus Nuncius = The Starry Messenger
About four hundred years before you read this sentence, a man called Galileo Galilei copied an ingenious device invented the previous year – the telescope – and turned it to the skies. He saw *amazing* things no-one had ever seen before – mountains and craters on the moon, a myriad stars glittering like dewdrops in the Milky Way, worlds spinning round other worlds… He proclaimed his glorious discoveries in a book called *Sidereus Nuncius* (or *The Starry Messenger* to you and me).

Like an old friend of mine once said, Galileo was "**the father of modern science**". His discoveries opened up whole new worlds, but more to the point the *methods* he invented to discover them opened up whole new *ways* of opening up whole new worlds. Galileo would have felt at home in a modern lab: our knowledge has moved on, but our methods and mindsets remain basically the same as his. (This friend of mine, by the way – German fellow named **Albert** – knew a thing or two about physics himself.)

Those fine folk at the United Nations have seen fit to designate this year, 2009, as the ***International Year of Astronomy*** in recognition of Galileo's achievement, and its humungus impact upon human culture.

My friends at the University of Hertfordshire have made a little film[1] about one of the more glorious incidents in my career, when I had occasion to run into Signor Galilei and his fabled telescope.[2] So before anything else, why don't you open some popcorn[3], sit back and watch their mind-blowing movie?

'scuse *me* while I kiss the sky,

Quicksilver

(a.k.a. The Starry Messenger)

1. They think it's fiction. Little do they know…!
2. And it's a good job for you all that I did, believe me.
3. Taking the opportunity to explain to your class the physics behind the popping, of course!

HOW TO USE THIS BOOKLET

The purpose of this booklet is to support *The Starry Messenger* film. It spells out the background science in much greater detail. It contains suggestions for class exercises and demonstrations all based around the work of the scientist characters in the film. After showing the film to your class, it can be used as a teaching resource to support your physics or astronomy course.

The booklet tells a story – all about Galileo's main achievements and their development at the hands of other scientists. This story has three main "themes":

I. The nature of matter. What is the Universe mostly made of? Are planets, stars and galaxies made of the same stuff as people, elephants and mangos? What are the mysterious substances called **Dark Matter** and **Dark Energy**?

II. The story of gravity. How our changing picture of gravity reflects our growing conception of physical law: Galileo *vs* Aristotle; Newton's theory; Einstein and warped spacetime. Gravity as a tool for studying the nature of astronomical matter.

III. Scientific method. The twin roles of **Empirical** and **Deductive** reasoning in science – *i.e.* ***Experiment*** constraining mathematical ***Theory***. Scientific scepticism and independent thinking – the evidence of the senses *vs* the word of authority. The uncertainty inherent in scientific results and their refinement over time.

Each major scientist character in the film has their own chapter. You may pick and choose whichever best supports your teaching needs. Each chapter is divided into three sections:

Notes outlining the work of each scientist, what they achieved and why it was important.

Class exercises – experiments and problems – based on the work of each scientist.

"Crib sheet" for teachers, containing solutions to problems and suggesting topics for further discussion.

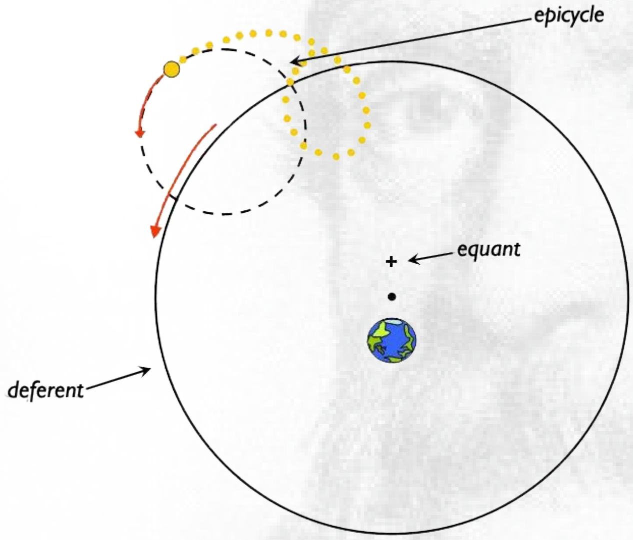
Feel free to photocopy whatever you'd like to distribute to the class (see copyright information on page 38). A full-colour PDF file of this booklet is also available at the following URL:

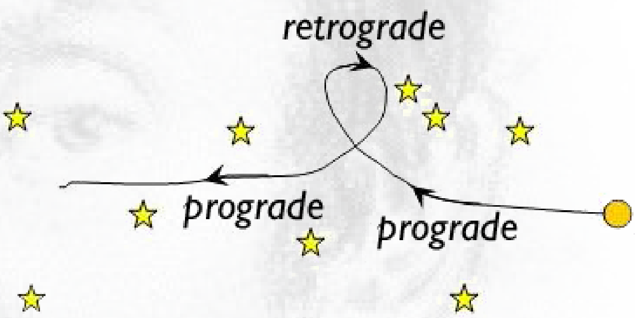
http://star.herts.ac.uk/starry-messenger

CONTENTS

GALILEO'S WORLD:
astronomy in 1600

The beginning of the 17th century was one of the most exciting and revolutionary periods in science. European scholars had busily been rediscovering the Ancient Greek knowledge transmitted to them by Arab astronomers. The accepted model of the cosmos was based on the work of a 2nd century Egyptian called **Claudius Ptolemy**. In this theory, the Earth lay at the middle of the universe, and all the other bodies – the Sun, moon, planets and stars – swirled around it on a compound of circular orbits (*below*).





*The great challenge of Greek astronomy was to explain the observed "loopy" motions of the planets relative to the stars (**above**). The "accepted" solution was the Ptolemaic model, (**left**) in which the planets don't orbit the Earth directly, but rotate around a point which does. Note too that the Earth was placed slightly off-centre: this was to explain small deviations which were later explained, by Johannes Kepler, to be due to the fact that the planets orbit not in circles, but in **ellipses**!*

In 1543, **Nicolaus Copernicus** had posthumously published a radical, rival *heliocentric* theory – *i.e.* one which placed the Sun, not the Earth, at the centre. He showed that, mathematically, this theory could explain the observed, loopy motions of the planets just as well as Ptolemy's – well, actually, it turned out to be a lot *simpler* than Ptolemy's, because there was *no need* for all those fussy epicycles, with wheels within wheels within wheels; it has just one orbit per world. This did not go down very well with those who thought the Earth, as the home of Humanity, should occupy a special place in the Universe.

It also conflicted with a favourite theory of Physics at the time, which was based on the ideas of the Greek philosopher **Aristotle**. In this theory, everything knows its place. Heavy, dirty, corrupt things belong on the Earth, and therefore they sink downwards, dragged toward Hell by their sin; the heavier they were, the faster they ought to move to the ground if dropped. Light, fluffy, innocent things belong in heaven, and therefore they float up to the sky to be one with the angels. Everything below the orbit of the moon was thought to be made of crude, earthly matter, subject to decay and death. Everything above was supposed to be made of a pure substance called *aether*, spotless and eternal, forever moving in that most perfect of geometric figures – the circle.

This was the way things were in the first decade of the 17th century. Then along came Galileo….

Scientific Method: mathematical theory and experiment

Until Galileo, theories about the nature of the universe were vague and hand-wavy (or *qualitative* to use the proper word). Galileo, building on the work of the Ancient Greek mathematician Archimedes[1], showed that quantitative descriptions not only fit the facts of reality amazingly well, but they can help you discover new, unsuspected facts too – because the maths does most of the work for you!

Perhaps most famously, Galileo invented a new type of argument called a *Thought Experiment* to deduce, from a logical point of view, his famous idea about unequal objects falling at *equal* rates (you can do it too – yes, really, you can! – see *Ex. page 10*). This amounted to showing the accepted theory – heavier things fall faster – led to a contradiction, and must therefore be nonsense.

Still, even this wasn't enough for Galileo. For him, ***experiment*** – that is, observation of isolated phenomena in the real world under controlled conditions – was the means by which theory should be constrained, honed and tested. The famous story about him dropping objects from the Leaning Tower of Pisa – to show to the assembled masses that lead balls or wooden ones, apples and melons, all fall at exactly the same rate – is possibly just make-believe. But it sounds like exactly the sort of thing he would have done (he liked showing off).

Galileo spent diligent years measuring the trajectories of falling objects. He was the first person to understand the importance of acceleration as a measure of motion. In particular, he observed that objects fall with a constant acceleration (9.8 ms^{-2} on the Earth's surface). He determined the path of projectiles – cannonballs for example – to be parabolic.

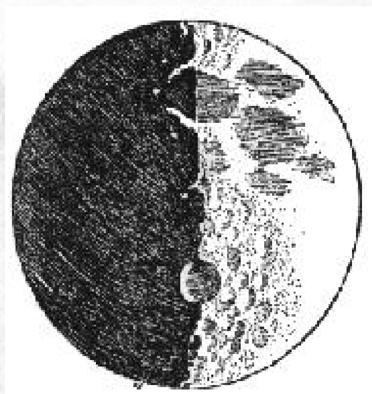
This is as far as Galileo had gone by 1609, but then he hit a stumbling block. Remember, according to Aristotelian physics, earthlike things belonged on the Earth, not in the sky (that's why they fall to Earth, silly!), so only a prize loon would even think that any laws of dynamics worked out in an earthbound laboratory could be used to describe the motions of the aethereal planets. They moved in circles: being perfect, what else could they do? Forget about parabolas and accelerations – they don't belong up there.

More Things in Heaven & Earth: the nature of celestial matter

In 1608, an optical device said to have been invented by a Dutch spectacle maker, Hans Lipperhey, became the talk of all Europe. This was the *telescope*. Galileo soon started making his own versions, and so assiduous a workman was he that very soon his models went to the top of every rich noble's Christmas list. In late 1609, Galileo first turned one of his telescopes to the skies. He was astounded by what was waiting there for him.

Mountains on the Moon

A replica of one of Galileo's sketches of the Moon, made in 1609, is shown below. Galileo was at pains to show that, far from the unblemished visage that an aethereal sphere was supposed to show, the Moon was *messy*. It's mottled, it's pock-marked, it's scarred with sharp shadows thrown across its face by immense mountain ranges gleaming in the lunar dawn. How could anyone think any more that celestial matter, the stuff of the heavens, was unsullied, aloof beyond our everyday experience and mortal comprehension? The Moon has a *landscape*, a more-or-less familiar, Earthly one, with mountain ranges like the Alps near Galileo's home in Padova. There was no longer any reason to think that they weren't made out of the same stuff. And if they're made out of the same stuff, they should obey the same laws of physics.



The Moons of Jupiter

The 10th January, 1610, was one of the most important days of Galileo's life. For the last few nights, he'd been watching what he called "starlets" near Jupiter.

1. Yes, he's the one famous for running naked down the streets of Syracuse yelling "Eureka!"

Their configuration appeared to shift between one night and the next (see *figure below*) though it wasn't clear whether that was just because Jupiter was moving in front of them. On the third night, however, in his own words, "*my perplexity was transformed into amazement*": two of the starlets appeared on the *opposite* side of Jupiter, and the third had *disappeared*!

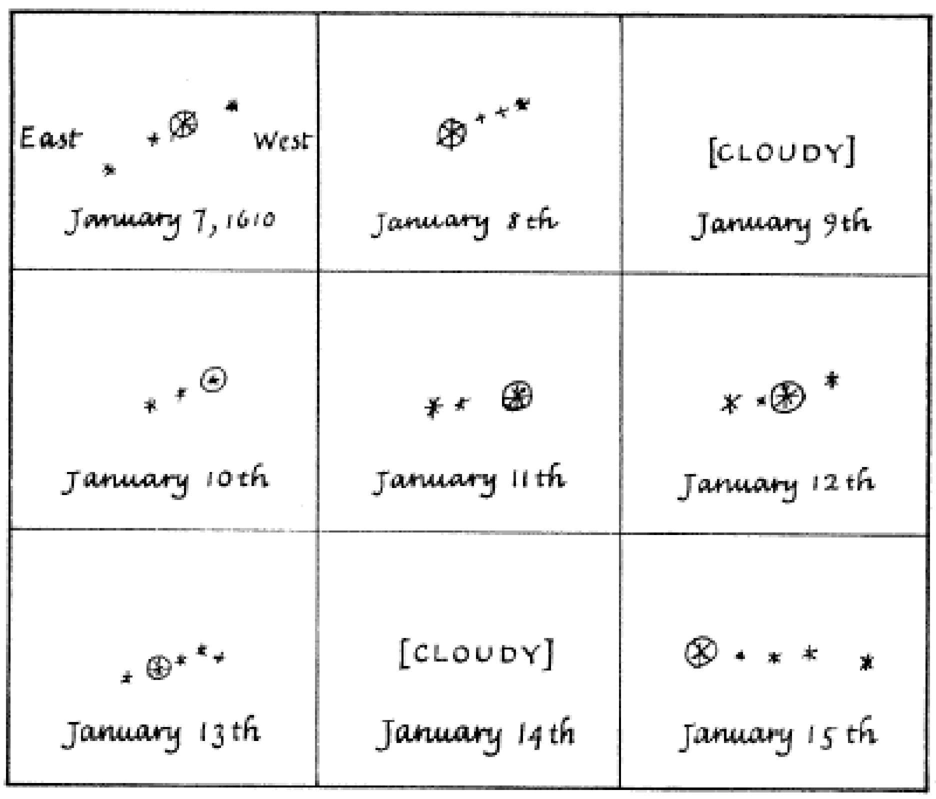
Now there was no doubt: **the starlets were moving around Jupiter!!!** This was shocking. It could mean only one thing: **NOT EVERYTHING ORBITS THE EARTH!!!** If objects can orbit another planet, **why can't all the planets orbit the Sun?** (We now know that the starlets are actually moons, orbiting Jupiter the way our Moon orbits the Earth. They are called the ***Galilean satellites*** in honour of their discoverer.)

Johannes Kepler had published a defence of the Copernican system, *Mysterium Cosmographicum*, in 1595, but he cited no *observational* evidence in its favour. Galileo's telescopic work therefore represents a major turning point. It established two significant points in favour of the new astronomy:

- The Heavens and the Earth are made from the same stuff. They obey the same laws: the laws of physics derived here on Earth apply throughout the cosmos. There's no reason to think that any part of the universe is any different from any other. There's no reason to think that the Earth occupies a special place at the centre.

- The Earth can't, in any case, be the centre around which all things rotate because other planets (namely Jupiter) have miniature systems of their own. If some things definitely don't orbit the Earth, why should we believe that everything else does? The Earth is orbited by the Moon, of course, but that doesn't make it in any way special, because Jupiter has moons of its own.

He published his observations in March 1610, in the work called *Sidereus Nuncius*, or (as I should think you know by now!) ***The Starry Messenger.***



Galileo's sketches of the "starlets" around Jupiter. On 7th January, 1610, he noted with curiosity the three objects stretched out in a line, along the plane of Jupiter's orbit. On 8th January, he noted that they had moved relative to Jupiter – or perhaps Jupiter had moved to the left relative to them? He could not be sure until 10th January [N.B. it was cloudy on 9th!], when two of the starlets had moved back to the opposite side of Jupiter, and the third had vanished. It now made more sense to suppose they were orbiting Jupiter very rapidly, occasionally vanishing as they moved behind it.

The Word of Authority *versus* the Evidence of the Senses

In 1600, **Cardinal Roberto Bellarmino** *(right)*, head of the Holy Office of the Inquisition in Rome and later canonised, sentenced the radical philosopher and hermeticist **Giordano Bruno** *(below)* to be burned at the stake for proclaiming (amongst other heresies) the existence of alien planets, worlds like the earth circling around other stars.

"Just as Aristotle said, the heavy one fell faster."

Galileo's telescopic discoveries placed him on potentially dangerous ground. Theologians identified the Moon with the Virgin Mary. It had therefore to be immaculate, a perfect, translucent orb *(right)*. Galileo's lunar seas, mountains and craters amounted to defilement, tainting it with the corruption of the Earth. This was a sin greater than the heresy of Copernicanism, which, at the time of *The Starry Messenger*, the Inquisition was still willing to tolerate.

The Immaculate Conception by Bartolome Murillo. The Moon is shown as a flawless sphere.

In 1616, however, Copernicus' heliocentric theory was deemed suspicious enough to warrant placement on the list of books banned by the Inquisition, pending review. During that year, Cardinal Bellarmino summoned Galileo to warn him not to defend the reality of the Copernican theory. Bellarmino's position was that putting the Sun at centre of the universe was *merely* a mathematical convenience. It made the sums easier to solve, but that didn't make it true – a piece of numerical sleight-of-hand, that's all. The distinction between the Copernican and Ptolemaic systems, both of which Bellarmino thought were merely calculational devices, was splitting hairs. As long as one did not fall into the trap of thinking that these theories represented the true state of affairs, the Inquisition was not too concerned.

Giordano Bruno.

Unfortunately for Galileo, he *really did* believe that the Earth moved around the Sun. Galileo was eventually summoned before the Inquisition in Rome in 1633, accused of the heresy of Copernicanism, and forced to repent. Unlike Bruno, Galileo recanted his views before the Inquisition. Galileo was sentenced to imprisonment rather than execution, although even this was later commuted to house arrest in Galileo's villa at Arcetri[1].

Ironically, perhaps, Galileo's confession saved both him and his science: had he remained stalwart and obstinate as Bruno, his works would very likely have been piled upon the censors' pyres and his achievements faded into the obscurity of hearsay. As it was, an initial ban on the reprinting of Galileo's works was lifted in 1718. Still, his confession was for the sake of appearance only. Upon leaving his trial, after being forced to admit that the Earth lay motionless in the centre of the cosmos, that the Copernican hypothesis was a mathematical abstraction only, Galileo is reported to have muttered "*eppur si muove*", meaning, "**and yet it moves.**"

1. Sadly, only days after her father's return to Arcetri, Galileo's daughter and *confidante* Virginia – by then known as Sister Maria Celeste – died aged only 34.

CLASS EXERCISE

Jumbo Bunjee – a Thought Experiment about Freefall

Pretend you live in a world where Aristotle's Laws of Physics are true. In particular, the Law that says:

∗ "Heavy objects fall to Earth faster than light ones"

is absolute gospel... Symbolically, if freefall rates are denoted by *R* and masses by *M*, then

∗ if $M(A) > M(B)$ then $R(A) > R(B)$.

Now let's pretend we're dropping various sorts of object off somewhere appropriately high: the Leaning Tower of Pisa, the Eiffel Tower, wherever. In particular, we're going to drop an elephant and a lute.

1. Calling the rate at which the elephant (named Giordano) falls $R(E)$ and the rate at which the lute falls $R(L)$, write an inequality involving $R(E)$ and $R(L)$, assuming (∗) to be correct (hint: elephants are much heavier than lutes!). Now drop them! Which one hit the ground first?

That was fun! Now let's do it again… oh hang on… this second elephant – let's call him Vincenzo – is a virtuoso lutenist and, as a last request, has asked whether he can play while he's on his way down! Fine…!

2. A lute-playing elephant sounds a bit suspicious, doesn't it? Perhaps it's a cunning plan on Vincenzo's part! He realises the lute's a lot lighter than he is, meaning, if he keeps hold of it… well, what does it mean? (hint: perhaps you could call it a paralute). Does Vincenzo fall faster or slower with the lute than he would without it? Write down an inequality for $E+L$ and E.

On the other hand… what if we think of the elephant+lute as a composite body? After all, elephants themselves are made up of lots of smaller parts (tusks, tails, toenails, etc.). Let's repeat the experiment with a hungry elephant called Isaac, who eats the lute for his breakfast (that's what you call an odd musical taste). As they say, you are what you eat, so Isaac plus lute just becomes a new, even bigger Isaac.

3. What's the mass of the composite Isaac+lute body? Using (∗), write down another inequality for $E+L$ and E. Does Isaac fall faster or slower than he would if he hadn't eaten the lute?

Does this fantasy world make sense? Does the rate at which elephants fall really depend on whether or not they've had lutes for breakfast? Galileo thought not, and concluded that the (∗) must be wrong.

4. Come up with an alternative to (∗) that does make sense, and doesn't contradict itself!

This type of argument, by the way, is called *reductio ad absurdum* which is Latin for "reduction to the absurd". And before we're too mean to old Aristotle, it's worth pointing out that he founded the theory of logic that underpins not only this sort of deductive reasoning, but even the principles of digital circuits inside computers...

1. No animals were harmed in this exercise of the imagination: in this fantasy world, elephants, like pigs, can fly, so they never actually hit the ground.

CLASS EXERCISE

The Man in the Moon – Who Needs a Telescope?

Many of Galileo's colleagues simply didn't believe their eyes when he showed them astronomical objects through his telescope. They assumed the blotches on the Moon were defects in the lens or dust on the eyepiece. They were able to defend their belief in an immaculate heaven by asserting that Galileo's equipment was flawed.

You probably find this surprising: surely it's well known that the Moon is all blotchy? We can all see the "Man in the Moon", can't we, even without a telescope?

Let's find out! Go outside next time the Moon's visible, and draw, as carefully and accurately as you can, what you see. Don't be swayed by pictures you've seen before – pretend you're seeing it for the very first time. Make several sketches, at as many different lunar phases as you can. Compare your results in class.

Observation 1: ________________________

Observation 2: ________________________

Observation 3: ________________________

Observation 4: ________________________

TEACHER'S CRIB SHEET

Jumbo Bunjee and The Man in the Moon

JUMBO BUNJEE: This exercise is identical (minus the elephants!) to the argument that Galileo himself used to show that the Aristotelian belief must be false. In the film, the older Celeste uses the same argument to teach her younger self the power of reason when it is honed and backed up by observation.

1. By (*), more massive objects fall faster, so $R(E) > R(L)$.

2. Expect controversial answers in here. Some might argue that Vincenzo will fall faster as soon as he grabs the "paralute", given the increase of the system's mass (see 3). However, the philosophy behind this exercise is to apply the Aristotelian law. The lute should fall slower than Vincenzo, so he ought, indeed, to be able to use it as a sort of parachute/"paralute" to ease his fall. Your intuition will probably resist this conclusion – but it does follow if you take (*) absolutely seriously. From Vincenzo's point of view, the lute will start floating above him, and, if he keeps hold of it, it will drag him back, so that $R(E+L) < R(E)$.

3. Masses just add up linearly, so the mass of Isaac plus lute is just equal to the mass of Isaac plus the mass of the lute: $M(E+L) = M(E) + M(L) > M(E)$. By (*), therefore, the rate of freefall of the composite has to be $R(E+L) > R(E)$.

4. By following (*), we've thus been led to two contradictory conclusions, (2) and (3). We can make the problem go away, however, if we turn all the inequalities into *equivalences*: $R(E) = R(L) = R(E+L)$. In other words, all objects fall at the same rate, regardless of mass, just as Galileo deduced and verified experimentally.

As we'll see later ("Eddington" chapter), Einstein took this line of reasoning about freefall even further, and deduced some even more profound conclusions about the nature of gravity…

∞

THE MAN IN THE MOON: The purpose of this exercise is to spark some discussion about the sociology and psychology of science. You could set your class some questions to debate, for example:

- To what extent is observation a skill that must be acquired through practice? How readily are we swayed by what our prior beliefs expect us to see? If you see something new, without any familiar terms of reference – for example if you'd never looked through a telescope before and were suddenly shown an image of Jupiter – how do you interpret what you're looking at?

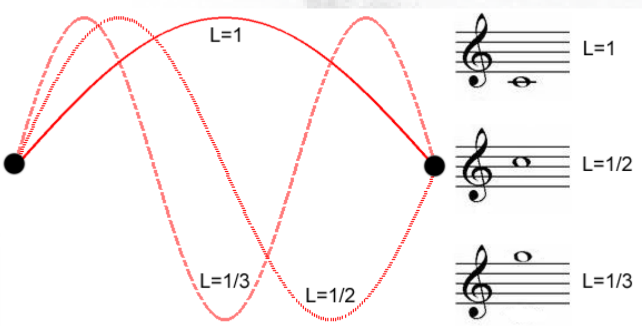
- To what extent does respect for, or fear of, our peers or our superiors affect the way we see things? To what extent does this prevent us from seeing new things, even when they lie right before us? (c.f. "The Emperor's New Clothes"!)

- The controversial philosopher of science Paul Feyerabend claimed that "*the Church at the time of Galileo was much more faithful to reason than Galileo himself, and also took into consideration the ethical and social consequences of Galileo's doctrine. Its verdict against Galileo was rational and just.*" Feyerabend characterized Galileo as an incautious opportunist, amplifying whatever evidence was required to support his case, rather than following any rigorous methodology. To what extent is this the norm in science? Can Galileo's enemies be forgiven for exercising scepticism before embracing his discoveries? Is it an attribute of genius to glimpse concepts that transcend conventional formulae and methods – to "think outside the box", throwing caution to the wind?

VINCENZO GALILEI:
music & scientific method

The Harmony of the World

Seems strange that music and astronomy are connected, but their marriage is actually very ancient. The Greek philosopher **Pythagoras** (c. 6th century BCE) is supposed to have discovered that musical harmonies are based upon simple numerical ratios:

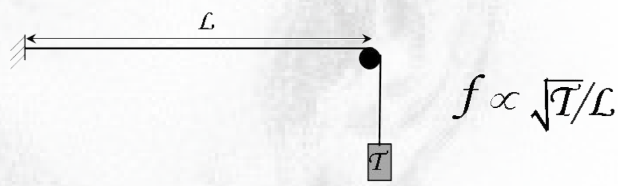


He thought that the planets wheeled in orbits governed by the same ratios, and so choired sweet harmonies as they whirled around. This Solar System Singalong became known as *The Music of the Spheres*. Nice idea – one that helped kick-start the whole of Greek philosophy – but things got a bit stuck for the next 2000 years. Until about 1600 everyone thought that these ratios were the be-all and end-all of music.

Vincenzo Galilei (1520-91) was a star lute player (author of a bestseller, "*Lute-Playing for Dummies*", or something like that), pioneering composer (just like Lennon & McCartney) and music theorist. He also tinkered about with pulleys and bits of string in his spare time, a strange hobby that garnered him the first truly new result in the science of acoustics since Pythagoras.

"my father discovered, tuning a lute is all a matter of mathematics"

The Greeks knew how the pitch of a sound depends on the length of a plucked string. It also depends on the *tension* – the force that stretches the string (which, in the apparatus belows, equals the weight of a mass hanging from a pulley holding the string tight). Everyone thought, following Pythagoras, that tensions



behaved just like lengths, that simple ratios of tensions determined harmony. Vincenzo carried out careful experiments to show this was *wrong*: the frequency of the note varies as the *square root* of the tension. This confused all those who were fixated on ratios – some very simple square roots (2 for example) *can't be written as ratios*.

You're probably thinking his name sounds vaguely familiar – so time to put you out of your misery: Vincenzo Galilei was Galileo Galilei's father. And it was probably Vincenzo's remarkable demonstration, that mathematics, guided by experiment, can harness the essence of harmony in ways that no-one had ever suspected, that inspired Galileo's quest to capture the *whole of nature* in laws and formulae. Vincenzo even went so far as to describe experiment as *"the teacher of all things"*: if methodical observation of phenomena contradicts authority – even one so eminent as Pythagoras – authority must be abandoned. If, as Einstein said, Galileo was the *father* of modern science, that must make Vincenzo… well, its *grandfather*.

Universal Gravitation:
ISAAC NEWTON

The Apple & the Moon

In 1665, Cambridge was evacuated as a precaution against the Great Plague, and Isaac Newton returned home to Woolsthorpe in Lincolnshire, where he worked in an isolation that can legitimately be called splendid. During the summer of 1666, he started to think about the nature of gravity. Although the story about Newton actually being hit on the head by an apple is probably rotten to the core, it was indeed perhaps a vision of fruit in freefall that inspired his revelation.

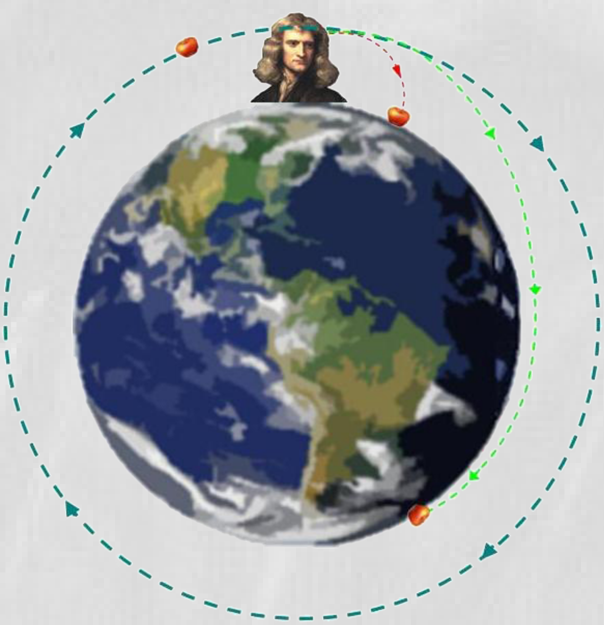
"The Moon's orbit about the Earth is a type of freefall due to gravity"

No matter where you drop it from: the top of a tree, the top of a tower, the top of a mountain, the apple will always fall to Earth. Earth's gravity seems to have no limit to its reach. What, then, if you travelled all the way to the distance of the Moon and dropped an apple? Surely it would still feel the Earth's gravity? So how about the Moon itself, then??? Newton quickly realised that: *the Moon's orbit about the Earth is a type of freefall due to gravity.*

If the orbit of the Moon about the Earth can be explained as an effect of gravity, why not the orbits of the planets about the Sun? Newton supposed that gravity was a FORCE acting between massive bodies. It was a Universal force – it wasn't just the Earth that exerted a gravitational pull, but all masses in the Universe act gravitationally on all other masses. Newton supposed that the natural state of motion of a body was a straight line – not a circle as the Ancient Greeks had thought. Any object will move in a straight line forever unless it is acted upon by a force.

Johannes Kepler had discovered that the planets orbited around the Sun in elliptical paths… so definitely not straight lines then! To produce elliptical orbits, Newton worked out that the gravitational force should fall off as the *inverse square* of the distance between two objects (R^{-2}).

It you think it's odd that an orbit can be thought of as a type of falling, imagine throwing a ball really hard. Usually balls follow a parabolic curve: they go up, they reach a peak, head back down and eventually hit the ground. The ball tries to travel along in a straight line, but the Earth's gravity pulls it down, and bends its motion into a curve. The harder you throw – the faster they're moving sideways – the further they get before they hit the ground. You could, in principle, throw a ball so hard that it stays in the air until it gets to China… or Australia… or so hard that it goes most of the way round the Earth and lands right behind you! or so even harder that… well, it doesn't come down at all! It just keeps on circling round and round the Earth. That's exactly what an orbit is. By the time the ball gets pulled down, it's moved so far that the Earth has curved away beneath it, and it just goes round in circles *(below)*.



Newton finally published his Laws of Motion in his *Philosophiæ Naturalis Principia Mathematica,* Principia for short, in 1687. It had a profound impact not only on the development of physical science, but on the whole of culture, helping to engender the Age of Enlightenment with its ideal of Rationality. The poet Alexander Pope praised Newton's achievement in his epitaph:

> *Nature and nature's lay hid in night:*
> *God said, "Let Newton be!" and all was light*

Optics

Newton's work in optics has also left a profound mark on astronomy: Newton invented a new type of telescope. Whereas the Galilean model used glass lenses to capture and focus the light, Newton's design uses a parabolic mirror (you can easily show, using the Law of Reflection, how this works – Exercise *Parabolic Mirrors,* p. 16).

This arrangement turns out to be much more convenient for astronomy. You need to make your *objective* (main lens or mirror) as big as possible. That way it collects more light (think of vessels left out in the rain: a bucket collects much more water than a thimble) so you can see fainter objects. And the wider they are, the finer the detail you can see. It's much easier to make very large mirrors than it is to make very large lenses. And because mirrors can be supported firmly at the back, rather than precariously round the edge like lenses, it's much easier to make steerable telescopes using mirrors. The largest optical telescopes in the world are based on variants of Newton's idea. Currently the record-holders are all around 10m in diameter, but there are plans to build optical telescopes with mirrors around 50m across!

Newton also showed that white light can be split up – *dispersed* – into a whole rainbow of colours, or spectrum, by using a glass prism. The prism refracts, or bends, the light by different amounts according to its wavelength, so white light, consisting of a cornucopia of colours, will be spread out. (This is another reason why mirrors make better telescope objectives than lenses: a glass lens will disperse the light and surround each object with an annoying spectral fuzz.) It was later discovered that spectra are not always smooth, but crisscrossed with dark absorption lines or bright emission lines, telltale fingerprints of individual elements. Astronomers study the spectra of stars and galaxies to learn what they are made of, how fast they're moving, what conditions are like within them, etc. We'll see, later, how this turned out to be a vital step in working out the nature of the Universe itself.

Isaac Newton and the Philosopher's Stone

Alongside the work now considered robustly scientific, Newton held a fascination for occult and esoteric wisdom. He attempted to discover the fabled Philosopher's Stone, or Chrysopoeia – a magical substance that would transmute ordinary metal into gold. He believed that God had granted secret knowledge to the ancient philosophers, who encoded their insights in secret wisdom. For example, Newton thought that Pythagoras had enciphered the Inverse Square Law in the doctrine of the Music of the Spheres. This belief followed from Vincenzo Galilei's discovery that changes in the tension (i.e. force) in a string are balanced out by changes in the square of its length – even though this wasn't discovered until 2000 years after Pythagoras! Just as there are seven tones in a musical scale, Newton also thought there should be seven colours in the rainbow – hence Red, Orange, Yellow, Green, Blue, Indigo, Violet.

It is easy for us to mock Newton, but let's not forget that we live in the squarely rational world that his Principia partly helped to create. Kepler, too, had sought to revive the ancient Pythagorean mysticism, trying every which way to fit the Music of the Spheres into the new cosmologies he developed. The path forward is not always clear, and it is the duty of a scientist to challenge the everyday way of looking at things, from every possible angle. New discoveries very often come from the strangest places.

CLASS EXERCISE

Parabolic Mirrors

This exercise demonstrates how a parabolic mirror can be used to bring light to a focus.

1. Using graph paper, draw in the *x* and *y* axes and the curve (a parabola). Make it nice and big. Use lots of points, and join them up as smoothly as possible.

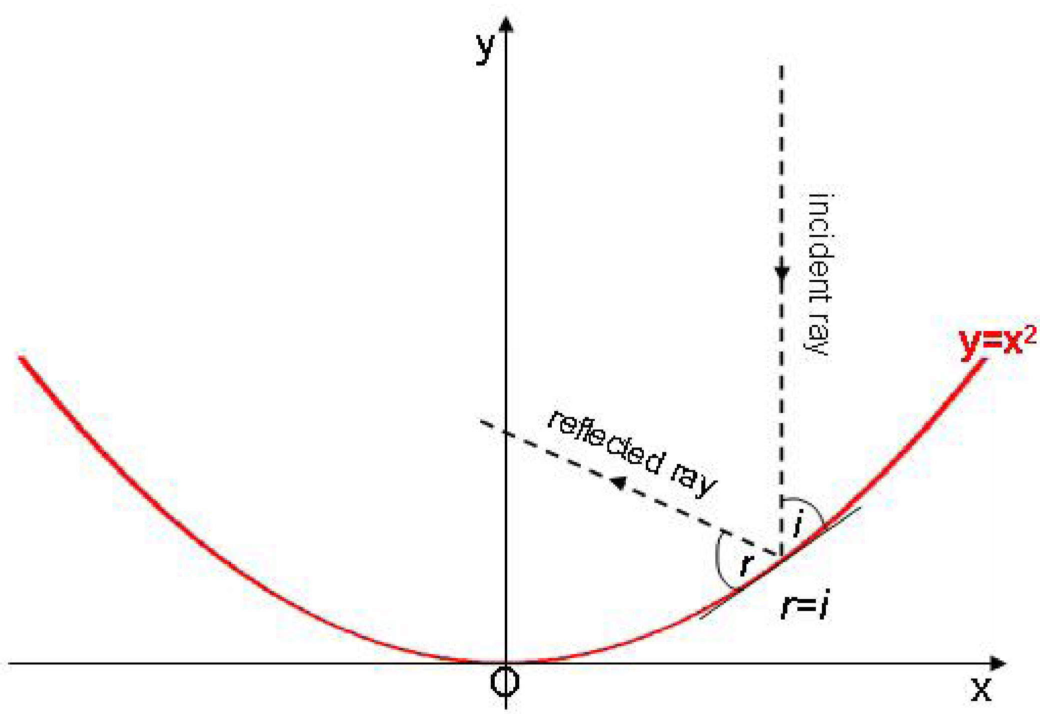
You're now going to draw a series of lines, all parallel to the *y* axis, and work out how they're reflected by the mirror. These lines represent rays of light coming from an object that is a very long way from the mirror (e.g., a star).

2. Pick a point with a large *y* value, and any *x* value you like. Draw a line, through this point, parallel to the *y* axis, until it hits the curve. This is the incident ray.

Do you recall the Law of Reflection? *angle of incidence = angle of reflection*. You're going to use this to determine the path of the reflected ray.

3. At the point where your ray hits the mirror, draw a tangent to the curve, as best you can. Measure the angle the ray makes with the tangent line. Now draw another ray, making the same angle but on the opposite side. This is the reflected ray.

4. Repeat steps (2) and (3) for a number of incident rays. Do you notice anything?



CLASS EXERCISE

Weaving a Rainbow

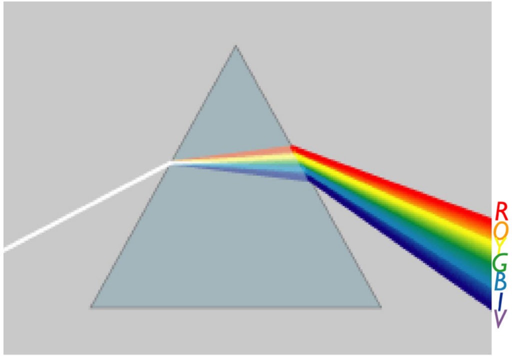
This exercise demonstrates **dispersion** of light, which is widely seen in the world around us.

Dispersion is the name given to the phenomenon where waves of different frequencies travel at different speeds through a substance, for example glass or water.

In nature, this phenomenon is seen in rainbows. The sun's light normally appears white; however, as the light passes through the water in the atmosphere, it is separated into its constituent colours.

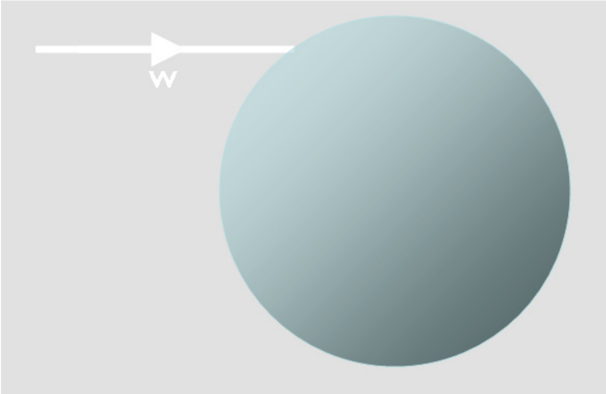
Prism Exercise:
Place a prism in the bright sunlight and turn it until you see a rainbow on the table or wall. How many colours can you see?

The red and blue components of the light travel at different speeds inside the glass so they have different distances to travel inside the prism. The red light "bends" less than the blue light as it has a longer wavelength.



If the angle the light makes with second surface is great enough, the light is reflected back inside the prism: this phenomenon is called total internal reflection, and is the principle that lies behind optical fibres.

Rainbow Exercise:
With rainbows, the same thing occurs as the light enters the water droplet. Can you complete the ray diagram for the light through a water droplet? Notice that the sun is behind the observer; so how does the rainbows light reach the person?



Extra: Sometimes we see a double rainbow. How do you think this differs from a single rainbow?

Extra: You can make a rainbow anywhere where the sun's light can be reflected this way. It happens in the mist above the waves of the ocean and above the pool of a waterfall. You can do this at home on a sunny day with a hose pipe on mist.

CLASS EXERCISE

Debate: Clipping an Angel's Wings

The mechanistic worldview ushered in by Newton's Principia was despised by the Romantic poets of the early 19th Century. In his 1819 poem *Lamia*[1], John Keats attacked the domination of Reason over Sensation thus:

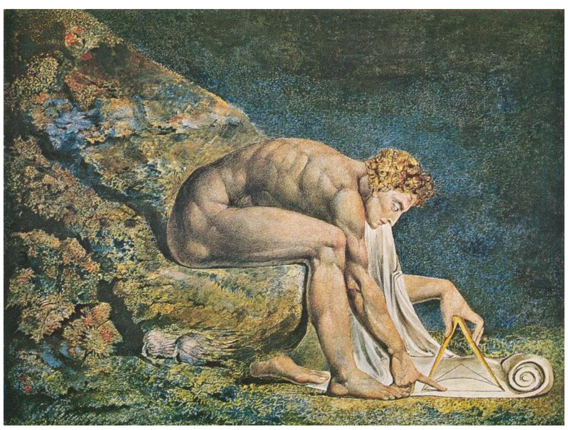
> *….Do not all charms fly*
> *At the mere touch of cold philosophy?*
> *There was an awful rainbow once in heaven:*
> *We know her woof, her texture; she is given*
> *In the dull catalogue of common things.*
> *Philosophy will clip an Angel's wings,*
> *Conquer all mysteries by rule and line,*
> *Empty the haunted air, and gnomed mine—*
> *Unweave a rainbow…*

Questions for debate:

- Does "philosophy clip an angel's wings"? Does understanding the origins of a natural phenomenon – for example, the mechanism for making a rainbow – make it any less beautiful? Does science relegate the sublime and mysterious to "the dull catalogue of common things"?

- If you grant that scientific comprehension makes nature no less beautiful, are we nevertheless in danger of forgetting the importance of poetry, art, religion, etc., in our relationship with the Universe? e.g. Einstein once said: *"Religion without science is blind; science without religion is lame."* Is a scientific account, by itself, sufficient?

- Many of the greatest scientists have been motivated by an abstract sense of awe and beauty, rather than by the practical benefits or technological spin-offs of their work. Do we, in the modern world, place too little emphasis on the intangible benefits of science for its own sake?



Newton, as painted by William Blake (1795). The painting demonstrates Blake's opposition to Newton's view of the Universe. This mindset is reflected in an excerpt from Blake's Jerusalem*:*

> I turn my eyes to the Schools & Universities of Europe
> And there behold the Loom of Locke whose Woof rages dire
> Washd by the Water-wheels of Newton. Black the cloth
> In heavy wreathes folds over every Nation; cruel Works
> Of many Wheels I view, wheel without wheel, with cogs tyrannic

1. Which just happens to star the god Hermes… - Q.

TEACHER'S CRIB SHEET

Parabolic Mirrors

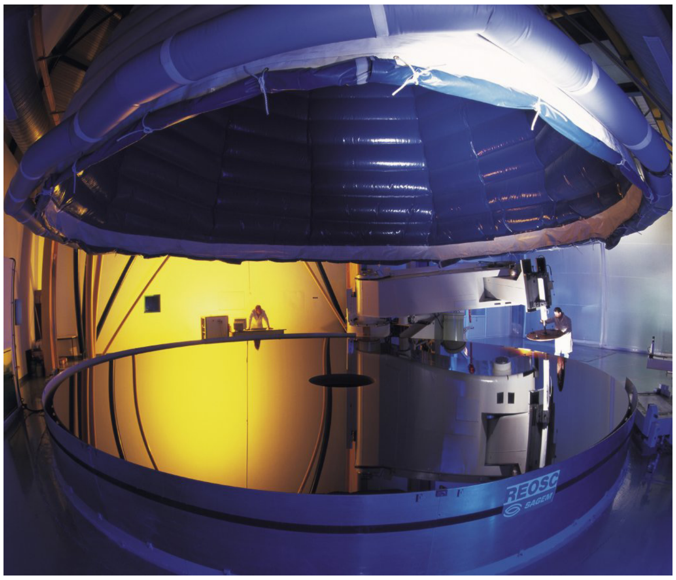
If you have a real parabolic mirror in your lab, dig it out and show it to your class. Let them come up and examine it while they are performing this exercise. Show them how the surface of the mirror is made by rotating a parabola about its axis of symmetry. Get hold of some plane mirrors, too, to illustrate how the image depends on the mirror's shape.

Before starting the experiment, you may wish to go over with your class some basic concepts in geometry and optics. Make sure they understand the basic properties of, and the Cartesian formula for, a parabola, which you may wish to contrast with the other conic sections (hyperbola and ellipse). Make sure they understand what is meant by a tangent to a curve, and how to find one. (An easy way to understand what a tangent is, is that it's parallel to the instantaneous direction of motion that you'd have if you were moving along the curve.)

Above all, revise the Law of Reflection with them. You can use the plane mirrors to demonstrate this very easily by shining an askew beam of light onto the mirror and noting that its reflection emerges at the same angle on the opposite side of the normal. You could tell the class that they can think of a parabolic mirror as consisting of lots and lots of very tiny plane mirrors, all arranged at different angles…

The answer to Step 4 is that the rays converge to a single point. The mirror focuses the light, just like a lens does. Do make sure that you have "one that you prepared earlier" to show the class that it really does work – in case theirs do not!

Finally, it's definitely worth telling your class that most large telescopes in the world today are based on this principle. Show them pictures of large optical mirrors such as the Gemini and VLT telescope, and the dishes of radio telescopes such as Jodrell Bank and Arecibo.



One of the 8.2m primary mirrors of the European Southern Observatory's (ESO) Very Large Telescope (VLT) undergoing its final polish. The VLT is based on Cerro Paranal in the Atacama desert, Chile, and consists of four 8.2m telescopes. *(Picture credit: SAGEM)*

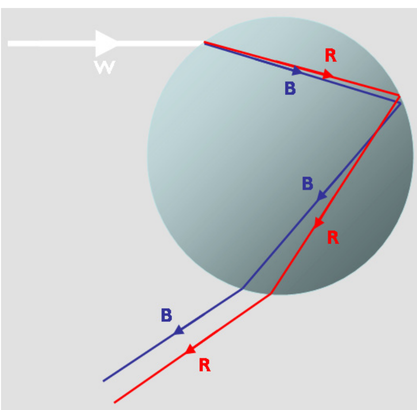
TEACHER'S CRIB SHEET

Weaving a Rainbow

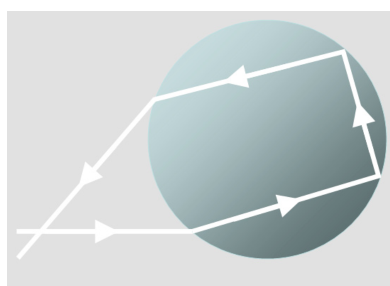
Prism Exercise
Do let your students experiment freely with prisms in sunlight first. Afterwards, you can show them a more formal demonstration of a prism using an intense, compact light source (e.g. a filament; if you don't have an appropriate compact lamp, pass the light through a narrow slit): project the light onto a screen several meters distant. Now place a lens in the optical path and move it back and forth until the light is focussed intensely on the screen. Place the prism between the lens and the screen, and move it about until you obtain a good quality spectral image.

You can demonstrate this with different light sources: e.g. (a) full-spectrum white light (b) filters of various colours in front of the white light (c) a gas discharge lamp, such as a neon, argon or sodium lamp.

In (a) you will see the full spectral continuum; in (b) you will see narrow sections only: point out how each colour is refracted by a different amount; and in (c) you will see discrete spectral lines corresponding to excited electrons in the gas atoms leaping down to lower energy levels. It's these lines, characteristic fingerprints of the elements, that allow astronomers to study gas in distant objects like stars and nebulae, and to measure the redshifts of distant galaxies (see chapter on Hubble & Humason).



The question "how many colours can you see?" is something of a sociological exercise. Physically speaking, there are an infinite number of colours in the spectrum, if by "colour" we mean the wavelength of the light. However, the phenomenological quality of colour that we consciously perceive depends upon much more than the wavelength (the nature of these *secondary qualities* or *qualia* – the "redness of red" etc. – a major problem in philosophy, was raised by Newton's contemporary John Locke in response to the former's experiments). As we explained in the main text, Newton insisted that there should be *seven* colours based on nothing more than his belief that the spectrum should match the intervals in a musical scale.



Finally, if you have a second, identical prism, you should attempt the "magic trick" of *recombining* the spectrum into white light! (Perhaps you could set your students the exercise of working out how this could be done…) Place the second prism behind the first, rotated through 180 and… *voila*!

Rainbow Exercise
In the simplest case, white light is dispersed on entering the droplet, reflects off the back of the drop, and is refracted again on entering the air.

Double rainbows result from *two* internal reflections. Note that this means that the order of the colours in the secondary rainbow is reversed, and the second rainbow is fainter.

TEACHER'S CRIB SHEET

Debate: Clipping an Angel's Wings

The critique of science – delight in the irrational, escape from the cold, iron grip of Reason – formed an important constituent of the rebellion of the Romantic artists in the 19th century. It is an extreme reaction; relations between Science and the Arts have not always been so strained (consider, for example, Pope's glowing praise of Newton quoted above). It would be very worthwhile collaborating with your colleagues from the English or Art departments to hold a class debate about this volatile, on-again-off-again marriage.

Much has been written on the subject. You might wish to read, for example, Richard Dawkins' anti-antiscience *Unweaving the Rainbow,* in which he counters Keats' critique on the side of science. Against that – in the interests of balance of course – you could give Mary Midgley's anti-anti-antiscience *Science and Poetry* a try.

And there were many poets besides Keats who expressed a similar view. Walt Whitman included the following in his 1900 collection *Leaves of Grass*:

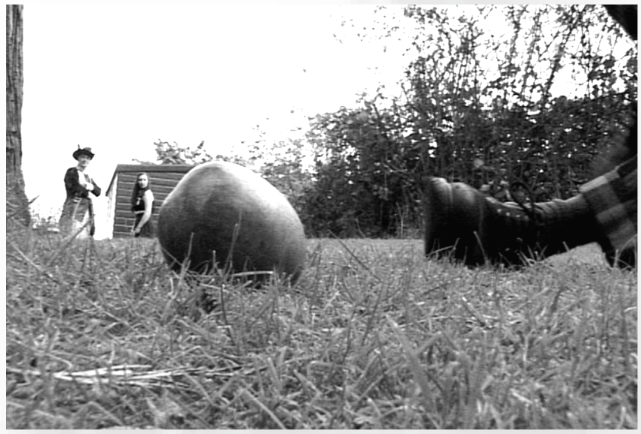
When I heard the learn'd astronomer;
When the proofs, the figures, were ranged in columns before me;
When I was shown the charts and the diagrams, to add, divide, and measure them;
When I, sitting, heard the astronomer, where he lectured with much applause in the lecture-room,
How soon, unaccountable, I became tired and sick;
Till rising and gliding out, I wander'd off by myself,
In the mystical moist night-air, and from time to time,
Look'd up in perfect silence at the stars.

The science fiction writer Isaac Asimov didn't like this, and published a polemic against it in *The Washington Post* (12th August 1979) entitled *Science and Beauty*. You can easily find reprints of this (google it! or find it in Martin Gardner's collection *Great Essays in Science*): copy it for your class, and see whether they agree with Asimov, or with Whitman.

References

Dawkins, Richard *Unweaving the Rainbow* (1998) Penguin ISBN 978-0141026183
Gardner, Martin *Great Essays in Science* (1997) Oxford ISBN 978-0192861948
Midgley, Mary *Science and Poetry* (2001) Routledge ISBN 0-415-27632-2

EDDINGTON &
Warped Spacetime



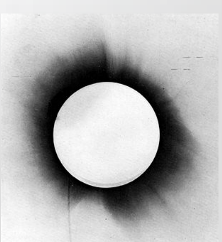
"That's one deflection they didn't predict"

Albert Einstein completed his *General Theory of Relativity* in 1915. It was a new theory of gravity, to rival Newton's. In Newton's theory, remember, objects "remain at rest or move in a straight line unless acted on by a force". Newtonian gravity is such a force.

Einstein's basic idea is astounding: ***gravity is not really a force!*** Objects under the influence of gravity continue to move in straight lines; it's just that space and time have become warped so that what is *really* straight ends up looking totally wonky… Massive objects change the laws of geometry around them (although a four-dimensional geometry involving space and time in an inseparable composite!), so that sometimes the angles of a triangle *don't* add up to 180 degrees, and parallel lines *do* intersect.

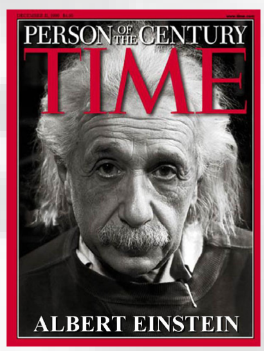
The Príncipe Eclipse and the Eclipse of *Principia*

By 1919, it was said that only three people in the world truly understood Einstein's theory. One of them was the British astrophysicist **Sir Arthur Eddington.** Eddington was committed to spreading the word about his friend Einstein's theory, and to looking for experimental verification of its validity. In 1919, a total solar

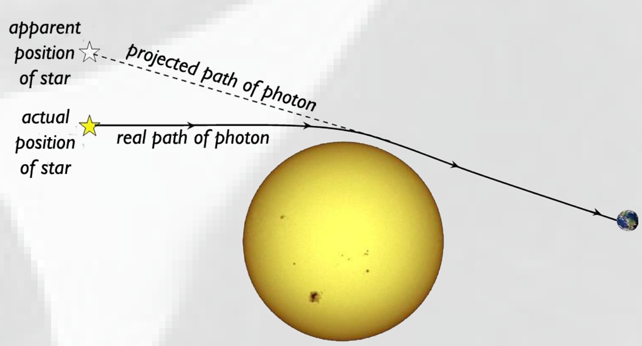


eclipse *(bottom left)* visible from the African island of Príncipe gave him just such an opportunity.

According to Einstein, the huge mass of the sun would warp space around it. Light from stars passing near the sun would be bent, and the stars would appear to have shifted position *(below)*. This happens all the time, of course, but the sun is too bright too see the nearby stars – except during an eclipse!

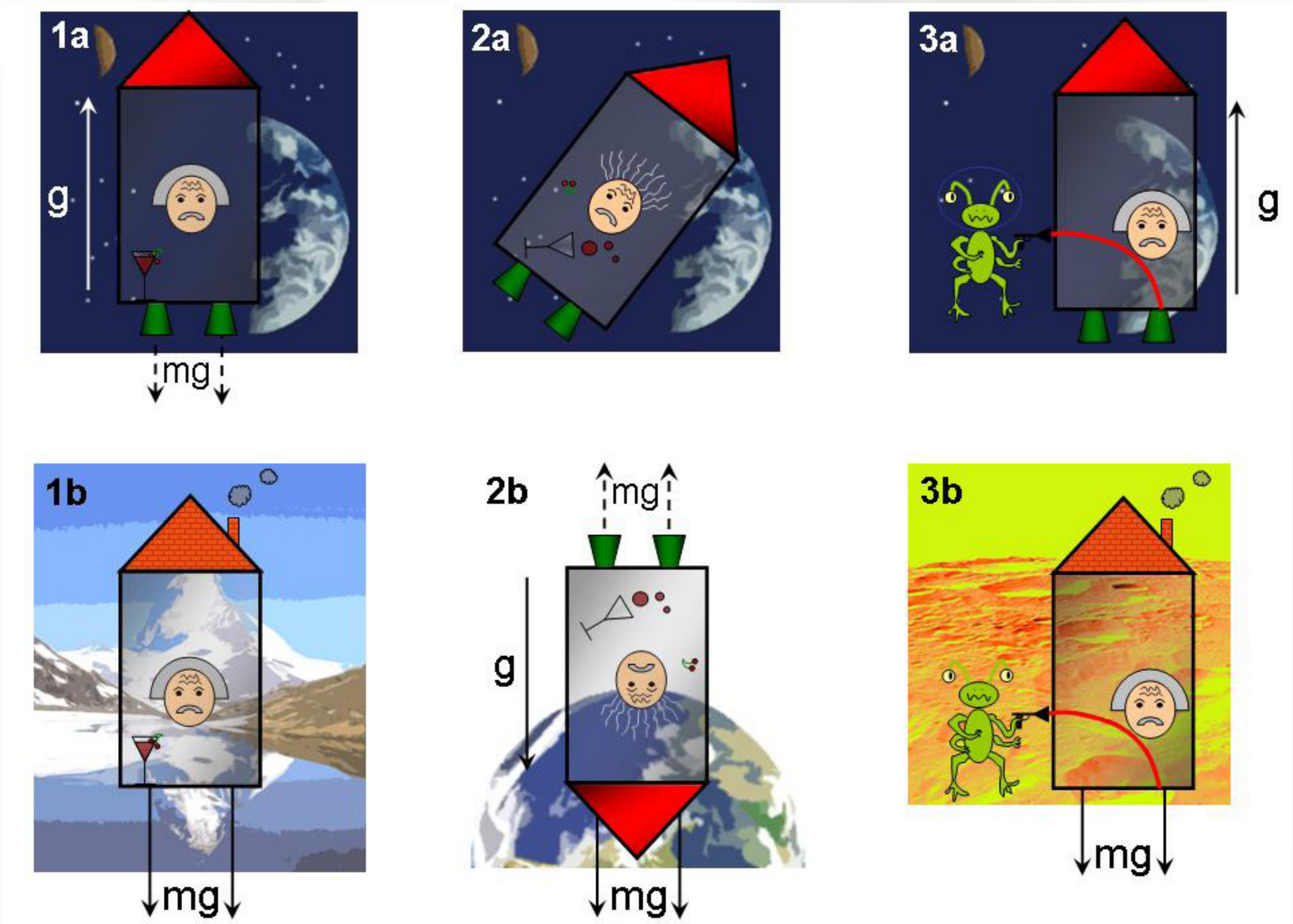


The eclipse enabled Eddington to measure the deflections of starlight close enough to the sun to compare the predictions of Newton *versus* Einstein. General Relativity won, and Einstein became an overnight celebrity.



"Behold, the Law of Freefall!" (again) – or Why Gravity Bends Light

Just like Galileo, Einstein started off from a ***thought experiment*** involving *freefall*. "Isn't it odd," (he pondered) "that *different* masses fall at *identical* rates?" After everything we discussed in the Galileo chapter, you're probably thinking Einstein had a screw loose (perhaps that's the secret of genius?). A quick trip on *Uncle Albert's Magical Space Elevator (below)* should make you think again:



1a. Uncle Albert is enjoying a nice cocktail in his rocket, **accelerating** through space at a constant rate *(g)*. Acceleration *upwards* presses you *down* with a force equal to *mass* ***times*** *acceleration* ($F = m \times a$) – just as you're thrown *back* in your seat when a car lurches *forward*…

1b. …or perhaps he's really back on Earth in his Swiss chalet, being pulled down by **gravity** rather than acceleration? He suddenly realises that **IT'S IMPOSSIBLE TO TELL!!!** (without looking through the window, that is…)

2a. Someone switched his engine off, and Albert is drifting about in space, far from any gravitational fields. His hair floats about and his cocktail slips out of his glass…

2b. …or perhaps he's actually **in freefall** above the Earth: the downwards acceleration cancels out the effect of gravity and he feels **weightless**. **IT'S IMPOSSIBLE TO TELL**.

3a. An alien tries to shoot Albert with his laser!!! Fortunately, the rocket is accelerating so fast that Albert has moved far past the ray by the time the light reaches him. From Albert's point of view, the ray looks bent.

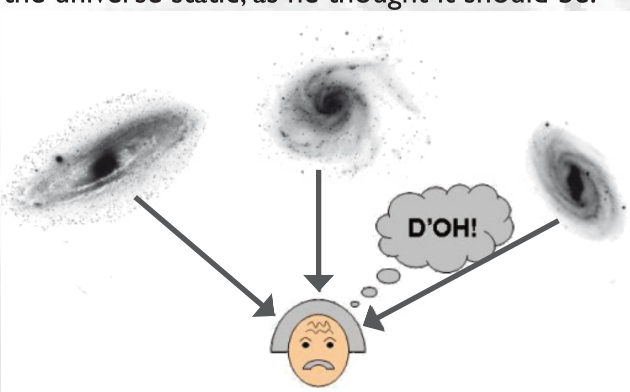
3b. …or perhaps he's actually on the alien's planet. So what's bending the ray of light? It must be the planet's gravity! But light is supposed to move in straight lines, isn't it? That means that, in gravitational fields, "straight" isn't really straight. Albert deduces that **GRAVITY BENDS SPACE**.

HUBBLE & HUMASON
Expansion of the Universe

"The further away the galaxies are, the faster they're moving away from us."

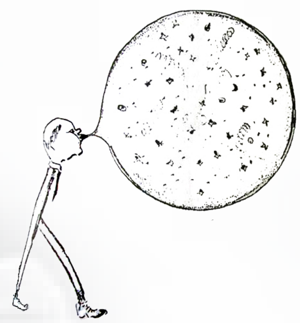
"Who tuk mah guum…?"

Cosmic Gum & Einstein's Greatest Blunder
Soon after deriving his theory of gravity, the *General Theory of Relativity* (1915), **Albert Einstein** used it to construct a theory of the structure of the whole universe (1917). The trouble was, it was unstable – it would quickly collapse under its own gravity *(below)*. Einstein introduced a universal repulsive field, the ***Cosmological Constant*** (denoted by the Greek letter lambda, Λ), to balance out the gravitational attraction, to keep the universe static, as he thought it should be.



Einstein's universe kept collapsing…

Soon after (1917), the Dutch mathematician **Willem de Sitter** derived a new solution to Einstein's modified equations, which was unstable in the opposite sense: the Cosmological Constant caused explosive (exponential) expansion! Einstein subsequently retracted the Cosmological Constant, calling it his "greatest blunder". (Don't forget it, however, for we shall meet it again…!)



The cartoon on the right, from a Dutch newspaper of the time, depicts de Sitter, in the shape of a lower-case lambda (λ) blowing up the universe as a balloon (or bubble gum perhaps). The original caption translated as, *"What blows up the bubble? It is the lambda. No other answer can be given."*

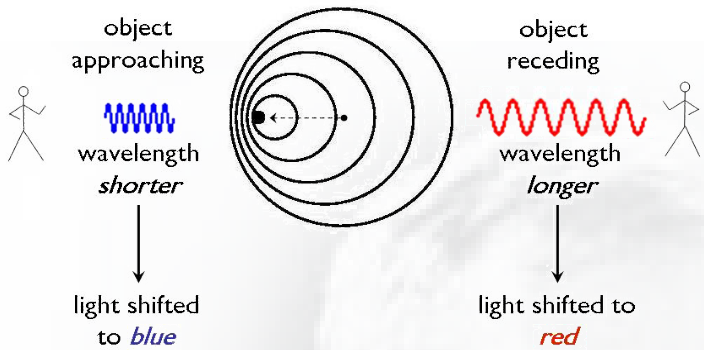
In fact, the Russian mathematician Alexander Friedmann showed, in 1922, that even without the Cosmological Constant the Universe would expand. So much for theory, but what did the observations say?

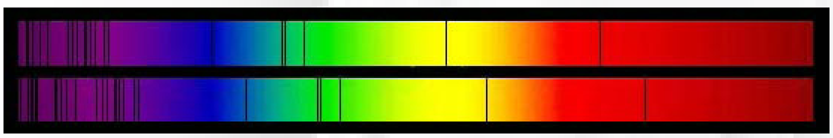
Island Universes
At the beginning of the 20th century, it was still not certain whether spiral nebulae lay within our own star system, the Milky Way , or were separate "Island Universes" – galaxies – in their own right. Edwin Hubble measured the distances to galaxies and settled the matter by showing that they lie far outside our own. Galaxies are now known that are so distant that it takes their light over 10 billion years to reach us.

In 1917, Vesto Slipher obtained spectra (plot of light intensity as a function of frequency or wavelength) of many external galaxies. Their characteristic absorption lines (decrease of the intensity of light at a given frequency or wavelength) all had longer wavelengths than when measured in laboratories on the Earth – they were all redshifted. The simplest explanation was that galaxies move away from us at vast (1000s of km/s!) speeds.

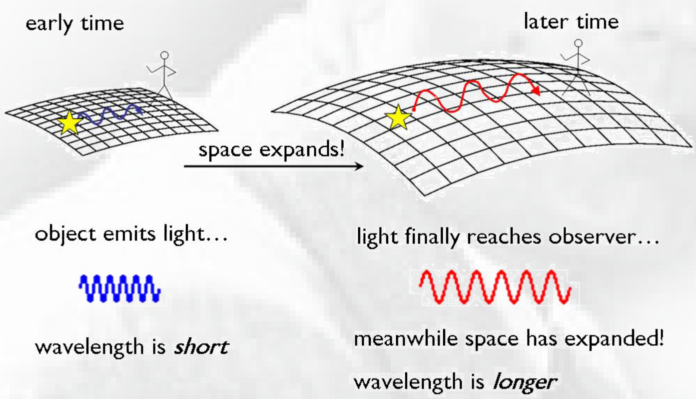
Two explanations of redshift:

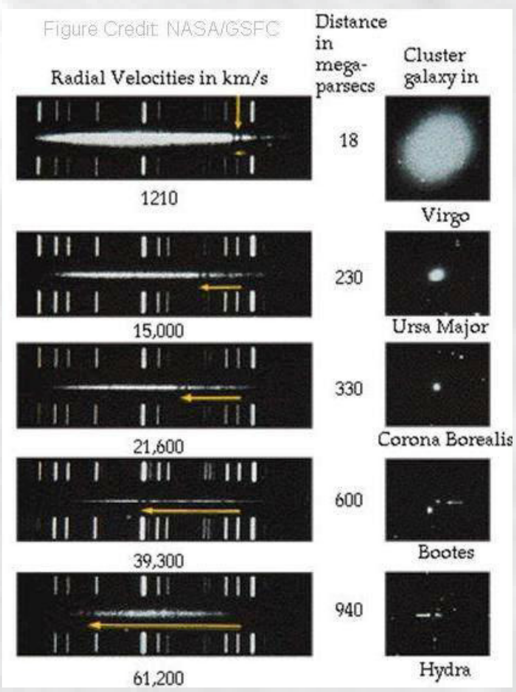
*(i) The **Doppler Effect.** Motion of a light source away from the observer makes the wave crests appear stretched out – the wavelength is longer, shifted to the red end of the spectrum.*





*(ii) **Expansion of Space**. The light from a distance galaxy takes so long to reach the observer that the Universe has expanded during its journey – and the wavelength is stretched toward red along with it.*





Through the 1920s, Hubble and his assistant **Milton Humason** measured the distances and redshifts of dozens of galaxies. They found something odd. As Hubble muses in *The Starry Messenger*, the **further away the galaxies are, the faster they seem to moving away from us** *(left)*. This is known as **Hubble's Law.**

This at first seems odd. Why should everything else in the Universe seem to be moving away from us? Didn't the work of Copernicus and Galileo demonstrate that there was nothing special about our place in the Universe? Actually, according to General Relativity, it's better to say that *space itself is expanding*, and you can use a very simple model of an expanding universe [Ex. p.27] to show that there's no preferred place in the cosmos: whichever galaxy you're in, you'll see all the other galaxies rushing away from you (a motion cosmologists now call the ***Hubble Flow***).

CLASS EXERCISE

Rediscovering Hubble's Law

The data – the distances and recession speeds of galaxies – originally reported by Hubble & Humason in 1929 are given in the table below. Note that given the large distances that astronomers deal with, we define a parsec as 3.262 light years or 3.086×10^{16} metres.

Galaxy Distance (Mpc)	Recession Velocity (km/s)	Distance (continued…)	Recession Velocity (continued…)
0.032	170	0.90	-30
0.034	290	0.90	650
0.214	-130	0.90	150
0.263	-70	0.90	500
0.275	-185	1.00	920
0.275	-220	1.10	500
0.45	200	1.70	960
0.50	290	2.00	500
0.50	270	2.00	850
0.63	200	2.00	800
0.80	300	2.00	1090

1. Plot a graph of recession velocity versus distance. [Such a graph is called a *Hubble Diagram*]

2. Find the best fit straight line through the points. Determine the gradient (slope) of this line. [This quantity, the gradient, is known as *Hubble's Constant* and is denoted by the symbol H_0]

3. Should the line go through the origin, or is there an intercept? Discuss.

4. What are the units of H_0? Work out the units of $1/H_0$, first in SI units, then in something more meaningful. What, physically, might this quantity correspond to? (Hint: think about how you can determine how long it will take something to reach you if you know its distance and velocity)

5. Why do you think that some of the velocities are negative (indicating that the galaxy is actually *blueshifted*, i.e. it is moving *toward* us), even though the galaxies are supposed to be receding from us to due to the expansion of the universe?

CLASS EXERCISE

The Ballooniverse

In the previous exercise you derived Hubble's Law – *i.e. a galaxy's recession speed is proportional to its distance* – from *observational* data. This exercise presents a simple demonstration of how to derive it *theoretically*.

Equipment:

Balloon (a black one, to look like space, would be nice, but any colour will do)
Adhesive spots (sticky stars would be *most* appropriate!) or coloured marker pens
String (ordinary string will do – Cosmic Strings or Superstrings just won't work as well)
Ruler (the measuring kind, not the monarch kind)
Stopwatch
Pair of lungs
A friend or two (believe me, it's *much* easier to do this in small groups instead of by yourself!)

Method:

1a. Partially inflate the balloon and stick/draw a bunch of spots all around its surface (but not too close together). These spots represent galaxies.
1b. Pick a spot – any spot. This is going to be your home galaxy. You might want to label it somehow. Make it nice and obvious – a bright colour or a flag (just don't stick a *pin* in it, alright!).
1c. Label all the other spots/galaxies – with numbers, letters, colours, any way you like.
1d. Measure the distance between your home galaxy and each of the others by stretching a piece of string between them and measuring its length with the ruler. Write down your measurements.

2a. Now let all the air out.
2b. Start the stopwatch – this is your *Cosmic Clock* – and simultaneously you need to…
2c. …start blowing up the Ballooniverse again as big as you like (but not so far that it explodes!) then…
2d. …freeze the Universe! Stop blowing and stop the watch. Take care not to let any air escape! Hold the end really tight, or tie it with a bit of the string.

3. Now measure the new distances between your home galaxy and each of the others. Write down your measurements – distance of each galaxy and the final time on the Cosmic Clock.

4. You should have two distances for each galaxy. Work out how far each galaxy has moved as the Ballooniverse expanded by subtracting the first distance from the second.

5. Work out the *velocity* of each galaxy by dividing this distance by the final time on the Cosmic Clock.

6. Plot a graph of *Velocity versus Distance* – a Hubble Diagram – for your spots/galaxies.

7. Fit a straight line to your graph. Work out the gradient of the line (which we'll call H).

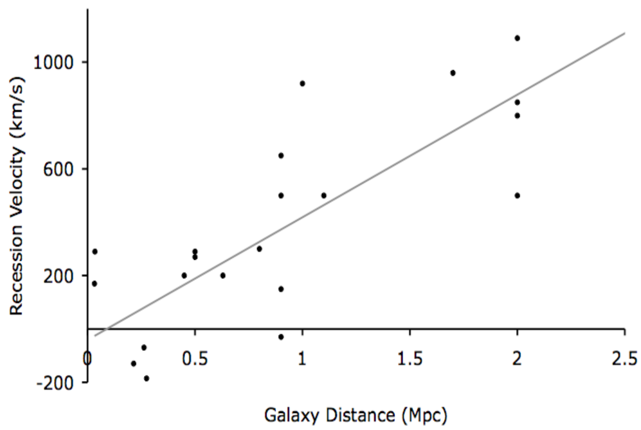
8. Find $1/H$. Compare with the final number on the stopwatch, and gasp in amazement.

TEACHER'S CRIB SHEET

Rediscovering Hubble's Law

1. You could get the students to plot the data on a computer, but pencil and graph paper is preferable. It should look like the plot presented here.

2. The first thing to note is how *bad* Hubble's data were! It is possible to fit a straight line, but the scatter is very wide. That's why it's worth doing the fit by eye: it forces the students to think about how uncertain real astronomical data often are, and how new discoveries are not always so obvious. Now, of course, the Hubble Diagram has been extended out to much greater distances, where the fits to the data become much tighter (see the next chapter, for example).



The best fit should come out as v (Mpc) 460 x D (km/s) or thereabouts.

3. Yes, the line should go through the origin. If it didn't, objects right next to you would be moving away at very high speed! Hubble's Law, in other words is:

$$v = H_0 D$$

4. This question is more advanced, but you could go through it with the class as a discussion. Recall that the dimensions of a quantity are expressed by square brackets [ ] so that:

$$[H_0] = \frac{[v]}{[D]} = \frac{\text{km s}^{-1}}{\text{Mpc}} = \frac{[\text{distance}]\text{x}[\text{time}]^{-1}}{[\text{distance}]} = [\text{time}]^{-1}$$

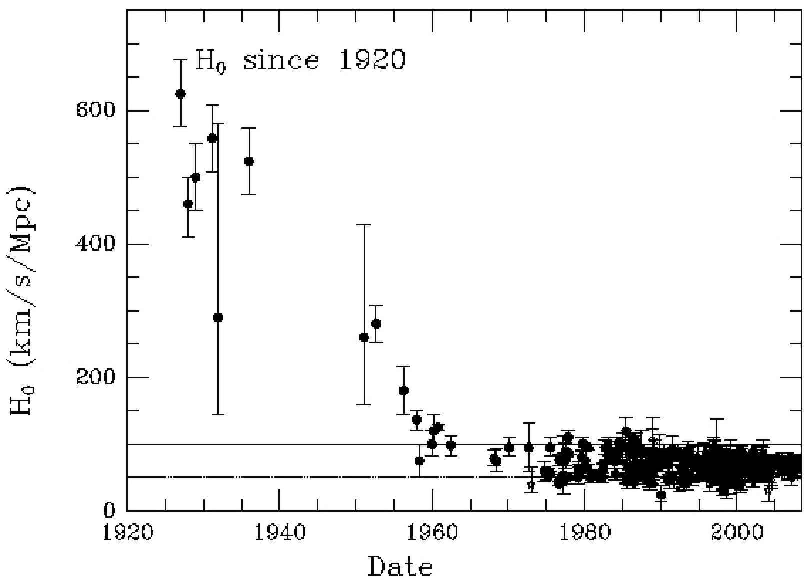
(N.B. pc measure distance Han Solo notwithstanding!) In other words, the dimensions of H_0 are 1/time.

$1/H_0$ can therefore be expressed as a time. Get the class to work it out from their best fit. It should come out as something like:

$$\frac{1}{H_0} \quad \frac{1}{460}\ \text{Mpc/km s} \quad \frac{1}{460} \text{x } 3.086 \text{ x } 10^{19}\text{s} \quad 6.7 \text{ x } 10^{16}\text{s} \quad 2 \text{ x } 10^{9} \text{ yr}$$

What does this mean? Well, imagine a galaxy at distance D. Hubble's Law tells us that it's moving away at velocity $v=H_0D$. The time it's taken to travel this distance away from us is $D/v=1/H_0$. Since this holds for all galaxies, everything in the Universe must have been located at a single point a time ~$1/H_0$ ago. In other words, **$1/H_0$ is an estimate of the age of the Universe**. Discuss with the class the implications of this, and whether they think their estimate is a meaningful one. How does it compare with other very long timescales that they might know about? (e.g., the age of the Earth).

5. Some nearby galaxies are indeed moving toward us. This is because they are gravitationally bound into a cluster called the **Local Group**, and as such they do not participate in the Hubble Flow, which only takes place on much larger scales. For example, the great spiral Andromeda galaxy, M31, orbits a common centre together with our Galaxy, the Milky Way, and it's thought that the two galaxies will actually collide in roughly 2.5 billion years or so!



This is one reason why Hubble's initial data were so bad. The history of Hubble's constant provides an excellent way of telling your class about the *uncertainties* involved in doing science, and how more and more precise experimentation is vital to confirming or disconfirming theories. Hubble's initial data gave an age for the Universe, 2 billion years, that was smaller than the age of the Solar System estimated from radioactive isotopes in meteorites, 4.5 billion years. The oldest stars in our Galaxy are thought to be about 10 billion years old. All this aroused scepticism about the supposed origin of the Universe in a Big Bang. However, since Hubble's time, many astronomers have refined his measurements and these problems have now disappeared *(graph above* - from the *HST H_0 Key Project/* John Huchra). The latest estimate for Hubble's constant is H_0= 71 km/s/Mpc, and the Universe is thought to be 13.7 billion years old.

The Ballooniverse

After the class has finished the experiment, you might like to discuss their findings with them:

- What did their graphs look like? [should be straight line through origin – like Hubble's Law].
- How does this apply to the real Universe? [Hubble's Law is a natural consequence of any uniform expansion]
- Ask them what they would have found if they'd picked a different home galaxy [should be identical]
- How did their estimates for the age of their Ballooniverse turn out? How did they compare with the times measured by the stopwatches? [should be the same]

"CELESTE HEAVENS"
Dark Matter & Dark Energy

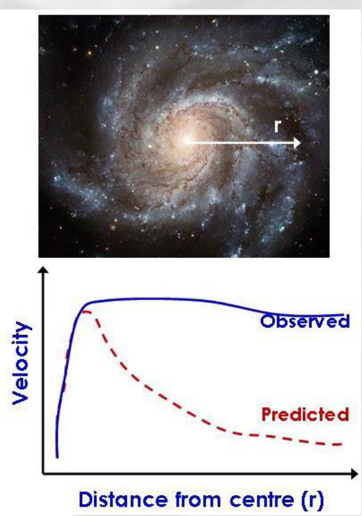
The single **biggest** and most *mysterious* question in modern astronomy is:

What is the true nature of Dark Matter & Dark Energy – substances that together make up over 90% of the Universe?

The simple answer is *"we don't really know!"* But we have some good – and rather bizarre – ideas. But let's first look at what we know about these weird substances, and what evidence we have that they exist.

Invisible Elephants

In the 1970s, an astronomy student called **Vera Rubin** measured the velocities of stars as they rotated about the centres of their home galaxies. According to Newton's theory, this rotation speed of a star is easy to work out if you know how many other stars there are exerting their gravity upon it. It's easy to count up the other stars because we can *see* them. Galaxies tend to be bright in the middle, and get more and more tenuous around the edges: orbital velocities should therefore rise to a peak near the centre, but fall off again in the outskirts. The measured speeds didn't do this. They stayed roughly constant out to very large distances from the galaxy's centre *(above)*… this means there must be **LOTS of mass that we don't see** making the stars swirl about. When I say LOTS I mean it: *ten times more* of it than there are visible stars in the galaxy! This mysterious, invisible stuff holding together galaxies gravitationally is called (for want of a better name) **DARK MATTER**.



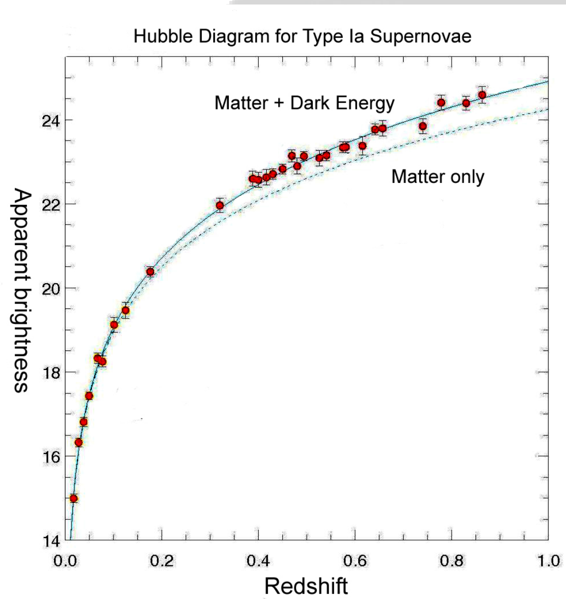
Other evidence for Dark Matter comes from studying *clusters* of galaxies. You can do the same trick, study the orbits of galaxies about each other, to work out how much mass there must be pulling on them, and (lo and behold!) it turns out to be *much* more than you'd expect if you just count up the visible light. There's also a very cunning technique called *gravitational lensing* which you can use to map the Dark Matter in a cluster. This uses the way its gravity bends the light from galaxies behind the cluster – just like Eddington's eclipse observations. See the prize-winning article *"Catching Invisible Elephants"*, reproduced overleaf, if you're interested.

The Revenge of Einstein's Blunder

Remember the Cosmological Constant, Λ? (I warned you it would make a comeback!) That extra repulsive term Einstein added to his equations to keep the Universe from collapsing – but later tried to sweep away underneath the carpet because he was so ashamed of it (presumably because it was so…repulsive…)? Well, turned out he was right all along, even when he was wrong!

In 1999, two bunches of astronomers were each studying the Hubble Diagram of a special sort of exploding star called a **Type Ia Supernova** in distant galaxies. What's so special about them is that they're all supposed to be exactly the same brightness – what we call a "standard candle". Think of light bulbs. A 100W light bulb will look as dim as a 10W light bulb if it's much further away. But if you know it's a 100W bulb, you can work out exactly how far away it is. Well, Type Ia Supernovae are like lightbulbs in space – except they're as bright as a billion billion billion billion 100W light bulbs so you can see them *much* further away. Far enough, in fact, that the expansion of the Universe has changed quite a bit since they went bang! So a Hubble Diagram made with these objects is potentially very, very revealing.

Until 1999, we all thought that the Universe was made mostly of matter and Dark Matter. You can work out exactly how this stuff affects the way the Universe expands. At least, we thought we could… Turns out that this model *doesn't fit* the Hubble Diagram of Type Ia Supernovae! The distant ones seem to be *more distant* than you'd expect from their redshift. Or, turning this on its head, they seem to be moving away *more slowly* than their redshift. Which means the Universe must have been expanding *more slowly* in the past. Which means that it's now expanding *faster* than it used to. Which means **the expansion of the Universe is accelerating!!!!**



Up: Hubble Diagram for Type Ia Supernovae, adapted from the Supernova Cosmology Project. Supernovae with high redshift – that is, high recession speed due to the cosmic expansion as they are so far away – do not fit the theoretical curve for a matter-only Universe. Instead, an accelerating expansion is needed, requiring a mixture of matter, dark matter and dark energy.

What on Earth (or not on Earth) could be causing space to blow up at an ever faster and faster rate? You already know the answer – remember de Sitter's bubble gum? It has to be the **Cosmological Constant**. "Cosmological Constant" sounds too dreary a name for something so important, yet so mysterious, and we now call it **DARK ENERGY**.

And there's lots of it. To get the acceleration observed, about 75% of the mass of the Universe has to consist of this stuff. Most of the rest – about 20% – is Dark Matter. All the stuff that you and I and cars and stars and planets and punnets and lutes and flutes and mangos and mountains and oceans and potions and moons and baboons are made of, all this makes up a mere 5% of the mass of the Universe. And we don't really know what the rest is.

Digging for WIMPs

The favourite idea for Dark Matter is that it consists of so-called "**W**eakly **I**nteracting **M**assive **P**articles", or **WIMPs**. Such particles are predicted to exist by particle physics theorists attempting to unify the fundamental interactions of nature – for example, by **Supersymmetry (SUSY)** models. Finding Dark Matter particles would solve one of the hugest puzzles in astronomy *and* one of the hugest puzzles in particle physics in one fell swoop.

WIMPs live up to their name: they don't exactly pack a punch. There are probably billions of them passing through you *right now*, but you'd never notice. If you pack enough stuff into one place, chances are, if you wait long enough, a WIMP *might* pick a fight with a particle of ordinary matter. Several experiments have been set up deep underground, in mines around the world – for example, in **Boulby Mine** in Yorkshire – to look for the carnage resulting from such a tussle – for example, a particle being shoved aside by a rare have-a-go WIMP. The mines help isolate the sweet, innocent detectors from rampaging cosmic rays, which, if you set the experiment up on the surface of the Earth, would simply cause a riot.

Even if you can't see that WIMPs are there, you can sometimes tell that something's missing. Imagine an invisible man at a party[1]. If you know how many sausage rolls you had to start with, and how many each of your visible guests has eaten, by looking at how many are left at the end you can not only tell that he must be there, but you can also learn something about the size of his appetite. The **Large Hadron Collider** in Geneva, a massive particle accelerator opened in September 2008, might be able to detect WIMPs indirectly in this way, by looking for missing energy and momentum in collisions.

1. This has happened to me lots of times – Q.

Zero-points and Phantoms

To produce global, accelerated expansion, Dark Energy has to be a fluid with *negative pressure* permeating throughout all space. We've already encountered one idea about Dark Energy – actually the simplest one – that it's a *Cosmological Constant*. It genuinely is constant, too: whereas ordinary matter gets diluted as space expands, the density of the Cosmological Constant stays exactly the same! One way of understanding the Cosmological Constant is that it corresponds to the underlying energy of the vacuum of empty space – sometimes called *zero-point energy*. Particle physics models predict such a zero-point energy to exist, but the theoretical value is **MUCH!!!** bigger than the observed size of Λ.

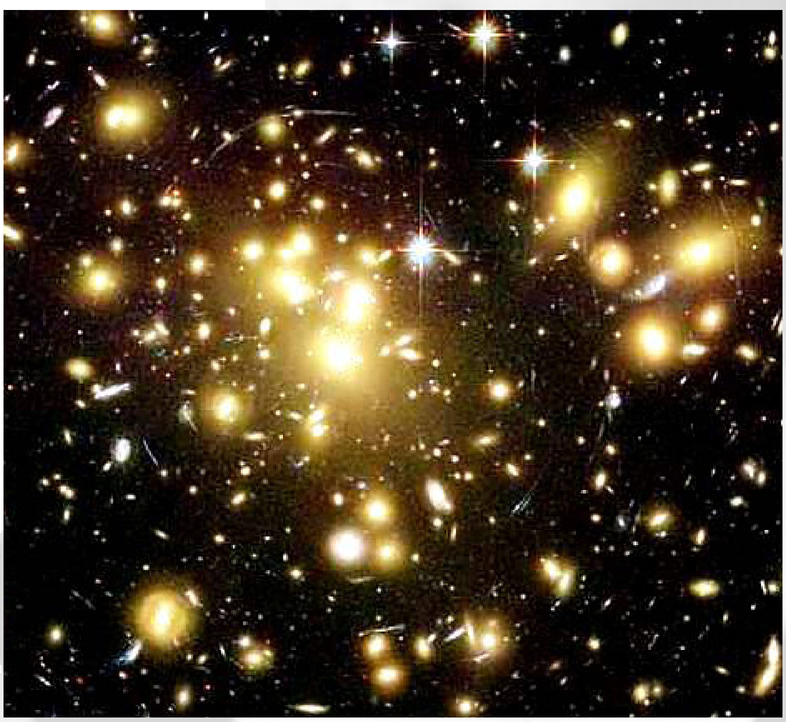
Another idea, that gets round this problem, is to have Dark Energy that isn't constant: it varies as the Universe expands. This is called, by cosmologists with a quirky sense of history, **Quintessence**, from the Latin term for the Aether, that most perfect of substances, out of which everything in the heavens was once supposed to be made (see Galileo chapter). How strange that things always seem to come full circle.

In some models, the density of Dark Energy – called **Phantom** energy – actually *increases* as the Universe expands. Since Dark Energy causes acceleration, the Universe expands ever faster and faster until – like bubblegum popping – it tears itself apart…. This apocalyptic state of affairs is called the **Big Rip**.

Postscript:
The Not-So-Distant Future of Physics

In *The Starry Messenger,* Celeste (the *new* Celeste!) discovers the nature of Dark Matter while she's studying for her PhD, and wins the Nobel Prize for her work some years later. This is fiction, but it is plausible: it is very possible that someone (*perhaps you!*) reading this booklet will make a crucial contribution to the discovery – which will be the most important scientific discovery of the 21st century. You could be a theoretical physicist predicting new families of particles with weird & wonderful properties. You could be an experimental particle physicist digging for WIMPs in a mine. You could be an astrophysicist studying the effect of dark energy on the acceleration of the cosmic expansion.

Whether or not it would lead to reality-manipulating technology and time-travelling, history-meddling post-humans from the future – well, that's a different story…



Hubble Space Telescope image of gravitational lensing in the galaxy cluster Abell 1689. The bright, fuzzy blobs are galaxies belonging to the cluster, one of the most massive known, which lies 2.2 billion light years distant. The arcs, however, are the smeared-out images of galaxies lying much more distant, billions of light years behind the cluster. Mammoth clumps of dark matter within the cluster bend space, according to Einstein's General Theory of Relativity. Light rays from the distant galaxies, travelling through the cluster, get warped, just as if they were travelling through a lens. The images of the distant galaxies therefore appear smeared out into circular arcs. By studying these arcs, astronomers can determine the mass and distribution of dark matter within the cluster – even though it's invisible!

Catching INVISIBLE ELEPHANTS

by Dr Meghan Gray, University of Nottingham

I HAVE a recurring dream in which there's an invisible elephant sitting on my bed. I can't see him, but I know he's there. I can tell by the way the springs bend under his weight, and by the way the crumbs from my morning toast have rolled into the middle.

A phenomenon astronomers call **gravitational lensing** is a bit like catching that invisible elephant. In recent years we have discovered that there is literally more to the universe than meets the eye: luminous matter, or objects that give off light, add up to less than 10% of the total mass of the Universe. That means a big fraction of the Universe must be made up of dark matter, but we can't see it directly because it doesn't shine.

How do we know it's there? We use the invisible elephant trick and a knowledge of gravity. The basic principle behind gravitational lensing is that light can be bent by the same attractive force that keeps our feet firmly planted on the Earth.

According to Einstein's theory of General Relativity, massive objects (say, a galaxy) can actually warp spacetime, just like my invisible elephant is making my mattress sag. So when light from a distant galaxy happens to pass through this warped bit of spacetime on its way to our telescopes, the light rays get bent. When we look at the image of that distant galaxy, we see that it has been distorted, or lensed. You can get a similar effect by looking at a candle flame through a wine glass end on. The candlelight gets bent as it travels through the glass, and instead of the flame we see strange patterns of distorted arcs and rings. (This effect is of course enhanced if you drink the wine first...)

In my case, the invisible elephants that are making the mattress sag are clusters of galaxies. Each of these mammoth objects is a swarm of galaxies bound together by gravity. And each one of these hundreds of galaxies is made up of billions of stars. It's the light from these stars that we see through our telescopes.

But even these hundreds of billions of stars make up only about 5% of a cluster's mass. Another 30% or so can be found in the diffuse gas that fills the space between the galaxies. This intracluster gas glows so hot that it gives off high energy X-rays, which we can also detect with satellites in orbit around the Earth.

But that leaves over half of the mass of the cluster unaccounted for! The mysterious missing mass is invisible in all parts of the spectrum, from X-rays to radio waves. However, with gravitational lensing we can trace this dark matter by looking through it at distant galaxies far behind the cluster.

Just as the light from the candle flame is bent as it passes through the wine glass, the images of these background galaxies are lensed gravitationally by the mass of the intervening cluster. Sometimes the distortion is so severe that normal looking galaxies are stretched and bent into arcs and rings – and sometimes we even see several mirror images of the same galaxy.

But even distortions not obvious to the eye can be detected statistically. By measuring how the shapes of the background galaxies have been changed by the lensing effect of the cluster, we can determine how much dark matter is there and map its distribution. Many distorted galaxies means that the cluster must be very massive. We can weigh a cluster billions of light years away just by taking its picture! *(See facing page, left)*

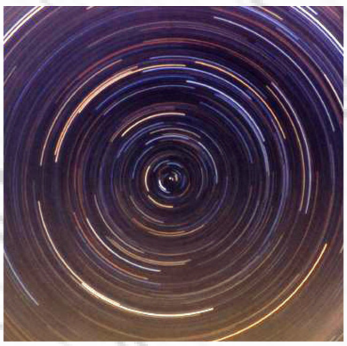
One of the frustrations of astronomy as a science is that although we have the entire Universe as our laboratory, we can't do anything to it. There's no way of fiddling with things and measuring the results as an experimentalist can. Instead, all we can do is point our telescopes and observe. The challenge then is choosing the most interesting things to look at and making the most of what we can see. And that's why gravitational lensing is such an important tool for astronomy: it allows us to see the invisible.

Reproduced by kind permission of the author.

THE STARRY MESSENGER
& Mythology

"The Imperishables"

In *The Starry Messenger*, The Imperishables are a hyperadvanced, post-human civilisation from the far future, with the ability to travel through time and, at some level, to manipulate reality itself. Their name comes from the Ancient Egyptian term for the **circumpolar stars** – the stars that never set below the horizon *(below left)*. To the Egyptians, the realm below the horizon – the *duat* – was the abode of the dead. The sun god had to suffer a series of trials as he passed through the *duat* each night, to earn the right to be reborn each morning in the east. The circumpolar stars were free from this eternal cycle of birth and rebirth, and were thus called the *ikhmu-sek* – the "imperishable stars".



The ***Empyrean*** – the Imperishables' abode – is the "highest heaven" of Dante Alighieri's epic poem *The Divine Comedy (right)*, a realm beyond physical existence, the abode of the "***primum mobile***" or "prime mover" of Aristotelian cosmology (Ironically, the Imperishables seem to have reinstated the mediaeval Aristotelian cosmology that Galileo strove so hard to demolish…).

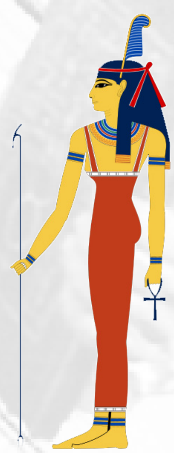
"Quicksilver"

Quicksilver is a popular name for the element mercury – suggesting its slippery, volatile nature. ***Mercury*** was the swift-footed messenger of the Roman gods; ***Hermes*** was his Greek equivalent, a quick-witted god of cunning and trickery, and an escort for the dead into the afterlife, represented celestially by the fastest and most elusive of the planets .

Quicksilver is also partly based on the Egyptian god ***Thoth*** – the god of wisdom, writing, time, magic, mystery and mischief, sometimes depicted as an ibis, sometimes as a playful baboon *(left)*. Thoth and Hermes later became the composite deity ***Hermes Trismegistus***, supposedly the founder of the occult knowledge that became known as "hermetic" – including the esoteric alchemical traditions of which Isaac Newton become a devotee.

"Pallas"

Pallas was one of the epithets of Athena, the Greek goddess of wisdom, and loyal, warriorlike protector of the law of her father, Zeus. *The Starry Messenger's* Pallas, though, has more in common with the Egyptian ***Ma'at*** *(right)* – goddess of order, truth, justice, and the motions of the stars. Ma'at was responsible for judging the fate of mortals after death: their heart would be weighed against a feather, and if light and unburdened by sin, their soul would be permitted to ascend to the stars to enter the eternal cycle of birth, death and rebirth (Such a reward awaits the "old" Celeste…).



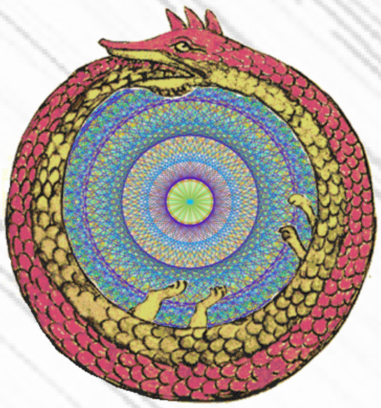
“The Grand Book”

The inspiration for The Grand Book comes from the famous line penned by Galileo in his 1623 work *The Assayer*: *“Philosophy is written in this grand book – I mean the Universe – which stands continually open to our gaze. But it cannot be understood unless one first learns to comprehend the language and interpret the characters in which it is written. It is written in the language of mathematics, and its characters are triangles, circles, and other geometrical figures, without which it is impossible to understand a single word of it; without them, one is wandering in a dark labyrinth.”* In *The Starry Messenger,* The Grand Book is *literally* the Universe – or, rather, Quicksilver’s personal terminal to the Imperishables’ ultimate computer, in which the Universe simulated with perfect accuracy…

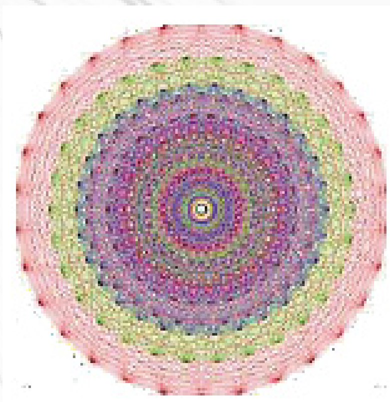
A book containing *“all wisdom of men and immortals”* appears in an Ancient Egyptian tale, *The Story of Setna.* It describes a quest for a magic scroll, ***The Book of Thoth***, which grants the wisdom of the gods to those who read it – but it is also cursed… The hieroglyphic inscription on the cover of The Grand Book identifies it, indeed, as the legendary *Book of Thoth.*

The Ouroboros

The serpent devouring its own tail, or Ouroboros, that adorns the rear cover of The Grand Book,



is a widespread image, appearing in Ancient Egyptian, Chinese, Greek, Hindu and Mediaeval European mystical traditions. It symbolises the perfect being that creates itself out of nothing (just as The Imperishables’ intervention in Celeste’s life enables her to discover the “Theory of Everything” which makes possible the whole of their civilisation….) The mathematical pattern wrapped within its coils is a pastiche of the E8



symmetry group (right), which underpins a “Theory of Everything” which made global news in 2007.

“Nede”, Land of the Gibbers

Nede is the “world without scientists” created when Celeste ripped up the Book, whose denizens are

called *Gibbers* – they “speak in tongues”, a mishmash of all the world’s languages (Gibberish, naturally). Like the “Lotus Eaters” in Homer’s *Odyssey,*

“In the hollow Lotos-land to live and lie reclined
On the hills like Gods together, careless of mankind
Where they smile in secret, looking over wasted lands,
Blight and famine, plague and earthquake, roaring deeps and fiery sands”
(Tennyson)

the Gibbers are besotted with a golden fruit, *soma*, which grants them every delight and all happiness – while their world falls to ruin around them. Nede is an inverse of Eden, where to eat of the fruit guarantees imprisonment within ignorance and delusion rather than expulsion and knowledge. Celeste is given a Herculean choice: ignorant bliss, or heroic hardship. Fruit granting wisdom, youth or a curse is very common in myth (e.g. from Norse mythology, Idûn and Loki – or is that Pallas and Quicksilver? – *right*).

DRAMATIS PERSONAE

Celeste Heavens ~ *played by* **Samantha Hickey**

Our very own "girl with the pearl", Celeste is either a timid, brow-beaten dogsbody or a confident theoretical physicist due to win the Nobel Prize in a couple of decades, depending which universe you're in.

Sam Hickey is currently studying for her PhD in Astrophysics at the University of Hertfordshire. Her research involves searching for some of the most distant galaxies in the Universe, looking back 13 billion years to the origins of cosmic structure. This is Sam's first major acting role, and she was also a Producer of the film.

Quicksilver ~ *played by* **Jon Crowley**

The Starry Messenger himself, Quicksilver is made to flit about through time performing "black ops" missions for The Imperishables, as a punishment for a failed rebellion against them. His techniques typically involve trickery and manipulation and he delights in the arcane.

Jon is a semi-professional actor and has featured in numerous stage and screen productions. He recently starred as Henry Higgins in the Abingdon Operatic Society's production of *My Fair Lady*.

Pallas ~ *played by* **Alice Williamson**

Pallas is a high-ranking Imperishable official responsible for ensuring that history runs the way they want it to. She is not above a little espionage herself, and has meddled often in human affairs, typically in the guise of the archetypal *femme fatale*.

Alice is studying for an interdisciplinary PhD in Music & Astronomy. Her thesis focuses on the historical relationship between the two areas in ancient China. Alice is a talented clarinettist and composer, and provided much of the artwork and music for the film.

Galileo Galilei ~ *played by* **Bob Chapman**

Galileo developed the foundations on which modern science is based. His belligerent stance against his academic rivals and against church doctrine earned him a house arrest, but secured a legacy for his methods and discoveries.

Bob has a PhD in Astrophysics and works on the biggest explosions in the Universe - Gamma Ray Bursts - and why they might not all be so big as everyone thinks. He is currently based at the University of Iceland.

Edwin Hubble & **Milton Humason**
~ *played by* **Ken Winter** & **Glen Parish**

Hubble *(below left)* was the most important observational astronomer of the 20th century, establishing the scale of the cosmos beyond our own Galaxy, inventing the taxonomy for galaxy types, and discovering the expansion of the Universe.

Humason *(below right)* originally drove pack-mules to the summit of Mount Wilson where he would watch the astronomers at work. He was eventually permitted to observe himself, and, despite having no formal qualifications, he proved himself an extremely competent astronomer and became Hubble's invaluable assistant.

Ken is studying for an MSc in Astronomy at the University of Hertfordshire, investigating the winds blown out by some of the most powerful stars. Glen is working on his PhD, studying the clustering of Distant Red Galaxies.

Sir Arthur Stanley Eddington
~ *played by* **Robert Priddey**

Eddington was one of the greatest theoretical astrophysicists of the 20th century, establishing a model for the structure of stars and how they shine *via* nuclear interactions. He was an early populariser of Einstein's Relativity, and later in life sought a "funadmental theory" to unify all of physics.

Dr Robert Priddey has a PhD in Astrophysics and is the Writer/Producer of *The Starry Messenger.*

Sir Isaac Newton ~ *played by* **James Collett**

Newton's contribution to physics is incalculable. He codiscovered calculus, using it to codify his three Laws of Motion, derived the Inverse Square Law of gravitation, investigated the refractive dispersion of light and invented the reflecting telescope.

Dr James Collett is a Principal Lecturer in physics at the University of Hertfordshire.

Eddington ~ *played by* **Headington**

Impresario and svengali, Eddington Arthur's path to fame began when he escaped from a travelling circus as a pup. He went on to produce some of the most memorable albums of the 60s and 70s.

Eddington's upstart nephew, Headington's badboy antics on voyeuristic reality TV show *Wildlife on One* earned him the status of tabloid antihero. This is his first true acting role.

A FEW LAST WORDS...

DVD Quick Start guide
The Starry Messenger DVD is best viewed on a standard widescreen (16:9 aspect ratio) PAL television with stereo speakers.

To play the movie, insert the disk into a DVD player and wait until the introductory animation has finished and the Main Menu appears. From the Main Menu, you may choose either to play the movie directly, or to jump to a particular scene. The latter would be useful if, for example, you wish to split the viewing between two lessons, or pause midway for class discussion.

To turn on the English subtitles provided, use the subtitle button on your DVD remote.

This means:
You are free (nay, *encouraged!*) to copy and distribute both this booklet and the movie.

under the following conditions:
- You must attribute the work in the manner specified by the authors (but not in any way that suggests that they endorse you or your use of the work).
- You may not use this work for commercial purposes.
- You may not alter, transform, or build upon this work.

Contact details
Do contact us if you appreciated *The Starry Messenger* film and this booklet. The entire project was completed on a very small budget, a feat that was only possible because the majority of contributors were willing to give their time & talent for no remuneration. Encouraging feedback would go a long way to securing *future* such projects.

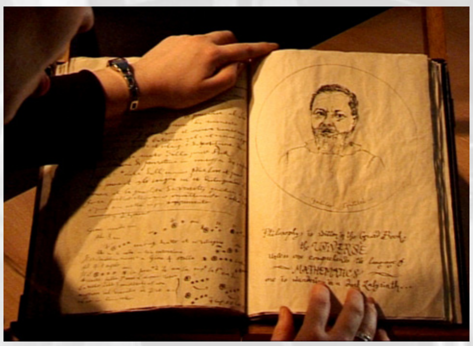
If you would like further copies of the DVD and booklet, please drop us a line; although we make no profit from this project, we may charge a nominal fee to cover reproduction costs.

All correspondence should be addressed to:

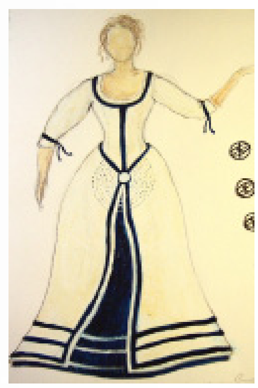
thestarrymessenger@gmail.com

The Making of
THE STARRY MESSENGER

The Telescope
The replica *(right)* of Galileo's first (winter 1609) telescope was made by UH Art & Design student Tina Moore, as part of her Final Year Project submission. Tina obtained images and designs of the original from the Galileo Museum in Firenze, matching construction techniques as closely as possible. The gilding around the leather was achieved using custom-made brass tools, designed to imitate the original pattern.



The Grand Book
The Grand Book was made by Franck Genet, with front and back cover illustrations and reproductions of Galileo's manuscripts by Alice Williamson *(left)*. The contents cover every conceivable topic – as the Book contains the Universe – text or pictures, real or imaginary! The pages were aged with coffee and bound irregularly to give the final "old book" look, and the cover is made of leather aged with sandpaper.



The "Very Nice Dress" & other costumes
Celeste's "very nice" (and very versatile!) dress was made by Mrs Gwen Goodger from a design *(right)* by Alice Williamson. All of Celeste's costumes have a "blue & cream" theme, just as Quicksilver's have a "green & white/cream" theme. As befits her role as (apparent) nemesis, Pallas' costumes invert Celeste's colour scheme, with a predominantly "red & black" theme. The historical costumes (Galileo, Newton, Eddington, Hubble, Humason) were hired from the National Theatre.

Locations
- *University of Bayfordshire*: University of Hertfordshire, main campus and Bayfordbury Observatory *(left)*
- *Nede, the World without Scientists*: SQ Environmental Water Hall Quarry, Hertford
- *Gibbers' "Downtown"*: Pinetum, UH Bayfordbury site
- *Renaissance Padova*: Private house, Baldock, Beds.
- *Galileo's residence*: Mill Street, Houghton, Cambs.
- *Newton's tree*: Tewin Orchard, Herts.
- *St Robert Bellarmine School*: Samuel Whitbread Community College, Shefford, Beds.

Booklet written by Robert Priddey

With contributions by Joanna Goodger

Booklet design by Gemma Hall

Cover artwork by Alice Williamson