Galileo's Legacy

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Introduction

I occasionally go into elementary classrooms to give presentations. If I do, I ask the teacher to get the students, the day before, to draw a picture of what they think the astronomer will look like. The results are interesting, but they often show an old, bearded man, looking at the sky through a spyglass. We owe that stereotype to Galileo.

But until 400 years ago, astronomers gazed at the sky with the unaided eye. Admittedly they had developed sophisticated measuring instruments such as astrolabes and sextants, but they had no capacity to gather light and show detail. In 1609, Galileo adapted and improved a recent Dutch invention – the spyglass – and turned it on the sky. Galileo's telescopic observations revolutionized our understanding of the universe, and our place in it. The telescope continues to be the means by which observational astronomy is done. And Galileo transformed astronomy from an abstract mathematical science to a physical one. He laid the groundwork for Isaac Newton's development of the laws of motion.

In fact, one could argue that Galileo developed "the scientific method" – the belief that a scientific theory is only as good as the evidence that supports it. One of my other IYA projects is developing support material for Ontario's revised secondary school science curriculum. It is remarkable how well Galileo's work illustrates every aspect of the modern school science curriculum!

International Year of Astronomy

So this year we are celebrating International Year of Astronomy, a year-long, world-wide, celebration of Galileo's revolution – his development and first use of the astronomical telescope. IYA is organized by the International Astronomical Union, and endorsed by UNESCO and the UN General Assembly. The motto is "The universe: yours to discover". That comes directly from the Ontario, Canada license plate!

Today, you are part of this celebration, along with people in 140 other countries. That entitles you to one of our trading cards; if you follow the instructions on the back, your name (and/or those of your loved ones) can be launched into space by the Canadian Space Agency. We also have beautiful commemorative stamps, released in early April 2009 during "100 hours of astronomy".

I'm a member of the IYA Canada Committee; two years ago, we developed our vision: "to offer every person in Canada an engaging astronomy experience – a "Galileo moment", as we called it – and to cultivate partnerships that sustain public interest in astronomy". Our definition of a Galileo moment was very broad – not just your first look through a telescope at the moon, Jupiter, or Saturn, but your intellectual excitement in wrestling with topics like the origin of the universe, or your deep emotional reaction to an astronomy-inspired piece of music or art.

Our secondary vision was that every professional and amateur astronomer in Canada would develop or join an IYA project that reflected their own interests and expertise. Over the last year, I had the great pleasure of working with Toronto's Tafelmusik Baroque Orchestra on *The Galileo Project: Music of the Spheres.* This program received rave reviews, and was certainly one of the best-ever examples of the fusion of the arts and sciences. Two weeks ago, we succeeded in having an asteroid named in their honour! And next year, the program is coming to California and other locations in the US.

Today, my goals are four:

1. To provide the scientific and philosophical background to Galileo's astronomical work;
2. To describe it's context, including the roles of Nicolaus Copernicus, Tycho Brahe, Johannes Kepler, and Isaac Newton;
3. To explain why Galileo's contributions to astronomy and physics are so significant; and
4. To outline, briefly, the subsequent development of astronomy, including our present conception of the universe.

In the Beginning

First: let's look at where astronomy was in the millennia before Galileo. From earliest times, humans used the sun and stars to navigate, to tell the time of day, and the time of year. The Inuit were particularly adept at this science. I heartily recommend the book *The Arctic Sky* by John McDonald, published by the Royal Ontario Museum. Prediction of seasonal climate changes, either by direct astronomical observation – as was done by many North American Aboriginal societies – or by counting days as we do, was arguably the most important technology of the time. It was necessary for hunting and agriculture, as well as for setting the date of ceremonial and religious events. They would have recognized the northern sky, for instance, by which every Girl and Boy Scout today can find north; you can also find your latitude from the angle of the North Star above the horizon, and use constellations such as The Great Bear as a clock to measure time.

Humans were awed by the sun, the source of light and life, and by the dark night sky, which was not obscured by the light pollution that we encounter today. They observed the daily motion of the sun, and the annual motion of the sun through the sky, including its annual motion north and south. Indeed, we celebrate Christmas in December (rather than in the spring, when scriptures imply that Christ was born) because that was when the Romans celebrated Saturnalia – the beginning of the sun's return from the south, and the lengthening of the day. But they didn't understand what caused the motions of the sun.

Names were attached to the stars and star patterns, reflecting the "popular culture" of the day, each culture having its own traditions [the Big Dipper is a good example]. We have inherited the star patterns of classical Greece and Rome, named after mythical characters and animals.

Moving against these star patterns were seven objects – five naked-eye planets, and the sun and moon. The seven days of the week are named after them (that's more apparent in the French or Italian version of the names).

They were associated with powerful gods – Mercury, messenger of the gods, Venus, goddess of love, Mars, god of war, Jupiter, king of the gods, and Saturn, god of agriculture and harvest.

It was only one step further to suppose that human characteristics and events could somehow be explained, or even predicted, by the positions of these seven bodies at your birth, and throughout your life. Astrology was born. The astrology that you read in the paper each day is descended from the Babylonians and Greeks. Different cultures had their own astrology, as they do today. But it's a pseudoscience. It doesn't work, except perhaps by the placebo effect. But it's interesting. And a surprising fraction of people read their horoscopes.

In classical Greece, philosophers began to wonder about the *nature* of the celestial bodies and, with the geometry of Euclid and others, they made great progress. They determined the size and shape of the earth and moon, and even knew that the sun was much larger than the earth. They rejected the idea that the earth revolved around the much larger sun for good reason – because they did not observe parallax, the apparent motion of the nearer celestial objects due to the motion of the earth. Parallax exists, but it was too small to be measured with the instruments of the time.

However, they tended to base their models on abstract reason, rather than on evidence. They assumed, for instance, that the paths of the heavenly bodies were circles, because the circle is the perfect geometrical figure. It was 1500 years before this mistaken assumption was corrected.

They didn't know what *caused* the motions of the sun, moon, and planets. They supposed that they were carried by a number of invisible spheres. The philosopher, mathematician, and mystic Pythagoras even proposed that the spheres might make music as they moved – the music of the spheres – audible not to the ear but to the intellect.

The philosopher Aristotle developed a model of the universe based on four elements – the earth at the bottom (and centre), then water, then air, then fire rising through the air, with the celestial objects made of a fifth element or *quintessence* which was perfect and unchanging. This model persisted until the time of Galileo.

Claudius Ptolemy developed the standard mathematical model of the earth-centered solar system, based on Aristotle's model, and on a complex system of circles. It correctly predicted the observed positions of the sun, moon, and planets.

In Europe, science went to sleep through the Dark Ages, and mediaeval times. Fortunately, the Islamic world kept science alive. Islamic astronomers continued to make increasingly precise measurements of the positions and motions of the sun, moon, and planets. The most famous was Ulugh Beg, scientist, mathematician, and sultan of Samarkand, and grandson of Tamerlane. He established an international centre of science and scholarship in Samarkand, with the finest observatory of its time.

Increasingly, the agreement between observations and predictions became more tenuous, putting more and more stress on Ptolemy's model. And cracks were beginning to appear in Aristotle's model, as a result of observations of the supernova of 1572 and 1604 AD and the comet of 1577 AD. The supernovas showed that the objects in the heavens *did* change.

Perhaps it didn't matter in the Dark Ages but, with the stirring of modern science in the Renaissance, theory needed to be accountable. Which brings us to Galileo, and five of the greatest scientists of all time.

The Renaissance and Revolution

First came *Nicolaus Copernicus*, a Polish priest, who proposed a sun-centered model of the solar system that was carefully thought out and presented, and simpler and more elegant than the Ptolemaic one. His famous book *De Revolutionibus* was published in 1543, the year he died.

Then came *Tycho Brahe*, aristocratic Dane, who built the finest astronomical observatory prior to the telescope (thanks to the support of the Danish court) and, using carefully-honed methodology, made accurate, reliable, comprehensive observations of the planets that strained Ptolemy's model to the breaking point. Incidentally, he was hot-headed, lost his nose in a duel as a young man, and wore a silver-and-gold prosthesis for the rest of his life. When his patron died, he fell out of favour with the ruling family, and retired in a huff to Prague, where he died. It's said that he died from a bladder infection; he had attended a royal banquet a few days earlier, desperately needed to relieve himself, but couldn't get up and leave until the king did. A week later, he died. It's also possible that he died of accidental – or deliberate – mercury poisoning. You may recently have read of plans to examine his remains for evidence of this.

Johannes Kepler was a mathematician and sometime astrologer who had worked for Tycho in Prague, and who was fascinated with numbers and shapes. He inherited (or stole, depending on who you believed) Tycho's data, and eventually realized that it showed that the orbits of the planets were not a complicated system of circles, but something much simpler – slightly elongated geometrical figures called ellipses. He noted a relationship between the size and period of the orbits, that he expressed in both algebraic and geometrical terms. These were his three empirical laws of planetary motion. He published them in *Astronomia Nova* in 1609, so we are celebrating that anniversary also. Like many scientists before and after him, he believed that this order was the work of the Creator. But he did begin to ask what physical processes might actually move the planets.

And then there was *Galileo Galilei*. He was born 15 February 1564, in Pisa, Italy, of noble but impoverished stock. His father, Vincenzo Galilei, was a lutenist, and composer of two books of madrigals, and other music for unaccompanied lute, and for lute and voice. He's even credited with pioneering the use of recitative in opera. At the same time, his countryman Monteverdi was beginning to revolutionize music, as Galileo would revolutionize science. He also made important contributions to the understanding of the physics of vibrating strings, such as the relation between their length, tension, and pitch. This must have been a significant influence on Galileo's later work.

Not surprisingly: one of Galileo's first interests was what determined the rate of swing of a pendulum – also a vibrating object.

Galileo first studied medicine, but transferred to math. He was a math professor at Pisa, then at Padua. He was a mathematician by trade but, perhaps because of his father's influence, his outlook on nature was based on experiment and observation, not on abstract math. He is the father of modern observational astronomy.

He was an early member of what would eventually become the Pontifical Institute of Science, but was originally called the Accademia dei Lincei, the Academy of Lynxes, so called because of their reputed sharp eyes. Galileo was a worthy candidate for membership!

By the way: he is usually pictured as an old man but, despite being a devout Catholic, he fathered three children out of wedlock. One is the subject of the award-winning book *Galileo's Daughter*, by Dava Sobel. Having these children, and several siblings to support meant that he was always on the lookout for ways to improve his position and increase his salary – as we will see later.

Galileo's troubles with the Catholic Church are widely known, and they were not fully resolved until the 1990's. I'm happy to say that Pope Benedict is a supporter of IYA, and participated in the official IYA kick-off in Italy.

Coincidentally, in 2009 we are celebrating a pair of anniversaries of someone else whose works have continued to generate conflict with some religions, especially in the US – it's the 200th anniversary of Charles Darwin's birth, and the 150th anniversary of the publication of *On the Origin of Species*.

Galileo also published several books. His *Starry Messenger* is a delightfully clear exposition of his telescopic discoveries, prefaced by an obsequious but necessary dedication to a potential patron. The book was rushed into print to establish his priority in his remarkable discoveries, though his telescopes were initially much better than those of his competitors. Keep in mind that there were no scientific research journals at that time, and certainly no Internet. Galileo had to write out several copies of his papers (or have it done by a scribe), and send them to other influential people by Pony Express, as it were.

His brilliantly-written *Dialogue on the Two Chief World Systems* is presented as a moderated debate between a proponent of the "old" system and the "new", and is a work of literature as well as a work of science. But it still got him into trouble with the Inquisition, and resulted in his house arrest for the last few years of his life.

Just to complete the list of the "big five" before we return to Galileo:

Isaac Newton was born within a year of Galileo's death. His accomplishments exceed even those of Galileo. He invented the reflecting or mirror telescope, which astronomers use today. He discovered that white light was a mixture of all the colours of the rainbow – an essential tool in modern astronomy. He co-invented calculus. He expanded Galileo's studies of the laws of motion, and organized them into his famous three laws. He developed the Law of Universal Gravitation – a simple relation that explained almost all observed motions in the universe. He published the *Principia Mathematica*, one of the monumental science books of all time – but definitely not one for laypeople. He was also an alchemist (or more fairly a primitive chemist), a theologian, and Master of the Royal Mint.

Back to Galileo

But now back to Galileo. Why is he considered one of the greatest scientists of all time, and perhaps *the* most important Italian?

To begin with: he developed and used the telescope for astronomy. This was not his only contribution to technology, but it was certainly his most significant. The telescope, along with the computer, is the basic technology of modern astronomy. The telescope provides two powerful advantages:

(i) it gathers more light than the eye can, and enables much fainter objects to be seen; and

(ii) it provides *resolving power* – the ability to see much finer detail

The power of the telescope is often stated in terms of its magnification or ability to make things appear closer, but that doesn't help without its light-gathering and resolving power. So don't buy a "trash telescope" from the department store – a telescope that claims 999 times magnification for $99.99!

After he published his first observations with the telescope, a few skeptics suggested that some of the newly-discovered celestial objects were not real, but were "manufactured" by the telescope. Their skepticism disappeared when they were finally able to see these objects for themselves.

His scientific discoveries are many and profound. He discovered four moons, circling Jupiter. According to Aristotle's theory, everything revolved around the earth; Galileo showed this wrong. Or to look at it another way: if the earth and planets circled the sun, why was the earth the only one with a moon? It wasn't. Galileo first named these moons after his patron, Cosimo II de Medici. Patrons were essential: keep in mind that there were no government research grants available at that time, but they are now called the Galilean satellites. His political strategy worked, however; he was immediately appointed to a new position as philosopher and mathematician to the Medici court.

He discovered that Venus – that bright object that you have been seeing in the west, after sunset in the first few weeks of 2009 – showed phases, like the moon, and their appearance disagreed with the predictions of Aristotle's theory, but agreed with those of Copernicus's. This is an exemplary application of "the scientific method".

He saw the planets as discs, rather than as starlike points of light. That's because the stars are *very* far away! He observed the strange appearance of Saturn – its rings – though the nature of the rings was not understood until many years later.

He discovered mountains and valleys on the Moon, which was therefore not a perfect celestial object, but a world something like the earth. He gave a clear discussion and explanation of "the old moon in the new moon's arms" phenomenon, which you see when the moon is a very thin crescent.

He studied spots on the sun: the sun too was not perfect, and it changed as sunspots came and went. Incidentially: Galileo was blind in his last years, and it is sometimes supposed that he went blind as a result of unsafe solar observing. But he wisely observed the sun by projecting an image onto a screen. But I learned from a colleague who is an expert on geometrical optics, that Galileo's *method*, as described in a letter he wrote, would not actually work. So there was something fishy somewhere.

He observed that the Milky Way, the faint band of light across the sky, was an infinity of small, faint and presumably distant stars – distant suns. No wonder they didn't show parallax! Similarly, he observed that several fuzzy objects in the sky were not clouds, but were actually clusters of dozens of faint stars.

He also carried out physics experiments, including a famous one in which he supposedly dropped objects of unequal mass from the top of the Leaning Tower of Pisa, to see if they fell at the same rate (they did). And he attempted to measure the speed of light – unsuccessfully, which is not surprising, considering that the speed is 300,000 km/sec. But he did discover the concept of "reaction time"! His experimental and theoretical work laid the groundwork for Isaac Newton's laws of motion, which eventually explained all motion in the solar system in one grand synthesis, and are still sufficient for spacecraft to explore the solar system. They also explained how the earth could rotate and revolve without us all flying off into space!

Since Galileo and Newton

Just to complete my list of the greatest astronomers of all time, after Copernicus, Brahe, Kepler, Galileo, and Newton:

The next would be *William Herschel*, a professional musician from Hanover who pursued a successful musical career in the tourist town of Bath, UK, while doing astronomy as a hobby at night. He built the biggest and best telescopes of his time. In 1781, he discovered the planet Uranus, and consequently received a salary from the king which enabled him to pursue astronomy full-time. He carried out major studies of stars, nebulae, and what we would eventually call galaxies.

You may notice that none of my top astronomers are women. Astronomy was not considered an appropriate activity for women, especially as it was done at night! But Herschel had a sister Caroline, who worked with him, and eventually worked independently, discovering eight comets, among other things, and becoming one of the foremost women astronomers ever – though rather controversial, as can be seen in commentaries from the time.

The next is *Harlow Shapley*, who determined the size, shape, and structure of our Milky Way galaxy, and our place within it – and was also the mentor to Canada's best-known and most beloved astronomer, Helen Sawyer Hogg – which makes Shapley my astronomical grandfather, because Helen Hogg was one of the great influences on my career.

The next is *Edwin Hubble*, Rhodes Scholar, athlete, lawyer, and eventually astronomer, who showed that there were other galaxies of stars like our Milky Way – a hundred billion galaxies, we now know – and showed that our universe of galaxies was expanding from its birth, now known to be 13.7 billion years ago. This he determined by the fact that the light waves, from these galaxies, were stretched (or reddened) by the expansion, proportionally to their distance.

And the last is a physicist and amateur violinist by the name of *Albert Einstein*. His General Theory of Relativity provides the framework within which we understand the nature and evolution of our expanding universe, originating with the Big Bang. In 2005, we celebrated the International Year of Physics, the 100th anniversary of the year in which Einstein published four papers, any one of which would have deserved a Nobel Prize – it was not the paper about relativity – too controversial!. This year, the astronomers are trying to outdo the physicists, and I think we are succeeding.

The Evolution of the Telescope

It's within this context that modern astronomical research is done. Galileo is the "father" of observational astronomy. The telescope is the primary tool, though in forms that might surprise Galileo.

Galileo's refracting or lens telescope actually had limited potential. To overcome the optical aberrations or deficiencies of lenses, it was necessary to make the telescope very long – and therefore cumbersome. And it was not possible to make lenses larger than about a meter in diameter; otherwise, they would sag and deform under their own weight.

Therefore, astronomers increasingly used reflecting or mirror telescopes, as developed by Newton. Photography, developed in the mid-1800s, enabled astronomers to take long time exposures that could store up light from much fainter objects. This required mountings for the telescopes that would allow them to stay pointed at their targets for many hours. By 1935, Canada had two of the three largest telescopes in the world, #2 being at the David Dunlap Observatory in Richmond Hill, Ontario, whose current status I would be glad to discuss during the question period.

Since then, there have been four major developments in the evolution of the telescope:

- Larger collecting mirrors, including ones with multiple mirrors to collect light.
- Sharper images, by locating telescopes in sites with clear, dark, steady skies; by the use of a technique called *adaptive optics* (I will give you an example, shortly); and ultimately by sending telescopes above the atmosphere into space (Hubble Space Telescope being the most famous).
- The use of more powerful instruments, notably the electronic camera which is almost a hundred times more efficient than photographic film.
- Telescopes sensitive to other kinds of light: infra-red, ultra-violet, X-ray, gamma ray, and radio.

Currently, Canada is a partner in three major telescope projects: the thirty-meter optical telescope, the Atacama Large Millimeter Array, and the James Webb Space Telescope – the replacement for Hubble.

But there has been another revolution, of a different kind: you can now buy a good telescope for a few hundred dollars. And for a few thousand dollars, you can buy a larger and better telescope, with a digital camera and computer, that will enable you to do front-line research in astronomy! I have spend much of my career, facilitating this kind of work by skilled "amateur astronomers" like the ones at this conference.

Our Universe – Galileo's Legacy

The universe, as we now understand it, is far greater than Galileo could possibly have dreamed of. The moons of Jupiter that he discovered are now known as the Galilean satellites; they have been visited, imaged, and studied by several spacecraft, including a NASA spacecraft named in Galileo's honour.

And I wonder what Galileo would think of the fact that the moon that he once studied with his telescope has now been visited by humans!

The sun is indeed the centre of the solar system, but there are now eight planets – the four larger ones with dozens of moons – hundreds of dwarf planets [Pluto has been demoted], asteroids and comet nuclei. The sun is moving around the Milky Way Galaxy, far from its centre, taking over 200 million years to do so. There are tens of billions of other galaxies, each with hundreds of billions of stars. But 90% of the mass of these galaxies is made up of some form of "dark matter", and many have super-massive black holes at their centres. Something we call "dark energy" is causing the expansion of the universe to speed up. Mysteries remain!

The image called the Hubble Ultra-Deep Field, conveys some of the excitement of modern observational cosmology; it shows galaxies so distant that their light has taken ten billion years to reach us, so they are seen as they were ten billion years ago. Astronomers can look backwards in time!

Many of the stars in our galaxy have planets, some undoubtedly like earth – but many quite different from the ones in our solar system. Quite recently, a team of astronomers – including Canadian astronomers – obtained the first images of a planetary system beyond the solar system, using the adaptive optics technique on the Gemini telescope. Indeed, Canadian astronomers are leaders in every area of astronomy that I have mentioned! In two recent surveys, Canada ranked #1 in astronomical research productivity!

The ingredients of life are everywhere, and most stars and planets have had more than enough time to evolve life, and intelligent life – perhaps even intelligent enough to contemplate the universe, and come to meetings like this one. If they do, we presently have the technology – radio waves – to communicate with such civilizations, anywhere in our galaxy. This is not science fiction!

Epilogue

But lest you feel humbled by this, let me paraphrase the words of the famous mathematician and scientist Henri Poincaré: "astronomy is useful because it shows how small our bodies, how large our minds". Astronomy is more than just scientific exploration and discovery. We should not forget the deeply human connections with the universe – history, philosophy, theology, art, music, the beauty and wonder of it all.