THE JULY LECTURES IN PHYSICS – 1992

Lecture 3

THE PC AS A WINDOW ON THE COSMOS

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Introduction

The sky is filled with an almost unimaginable variety of bizarre objects. Study of these objects is very important, since every possible physical phenomenon, no matter how rare or exotic, is sure to be going on somewhere out there! However, even a basic understanding of what goes on in the sky is hampered because of the sheer complexity and immense scale of our universe. It is difficult to get the 'big picture'. The purpose of this lecture is not so much to reveal anything new about what goes on in the sky, but to illustrate some well known phenomena through the window of the PC screen.

The Sky from the Surface of the Earth.

Let us begin with our own solar system. Although evidence is trickling in frustratingly slowly, it seems that our solar system is not unique in the universe. The most recent report of evidence for a planet orbiting another 'star' described a series of measurements of minute fluctuations in the normally rock–solid frequency of a pulsar. That such an unlikely object as a pulsar should have a planet in orbit around it is remarkable. This suggests to me that solar systems are likely to be common objects. However, for at least the indefinite future, we will not have anything like the amount of information about another system as we have on the one we inhabit.

Our solar system presents a confusing picture when viewed in the sky from the surface of the Earth. This is because our view is from a rotating reference frame. It took a long time, with many painstaking observations, before the Earth's rotational and orbital motions could be untangled from the apparent motions of the stars and planets. As an example, let us first look at the view of the sky from Melbourne. Most of us are likely to be city dwellers and are probably a little unfamiliar with the appearance of our own patch of sky!

Each night, the stars in the sky follow a circular path around the south celestial pole. This point is directly above the south rotational pole of the Earth. Stars close to the south celestial pole never set, their circular paths are relatively small and are always above the horizon. Others, further north, follow larger paths so that they rise and set each night. Still others, that follow circles near the north celestial pole, never rise at all and lie perpetually below the horizon.

Seen from the North Pole (that is the rotational pole, not the magnetic pole) the stars all follow circular paths around the celestial pole, which lies directly overhead. By coincidence a star lies very close to this position and is consequently known as the pole star, or Polaris.

The sky over Melbourne at the time of this lecture. From 'Skyglobe'.

All the stars that are visible never set. Of course half of the stars in the celestial sphere lie perpetually below the horizon. From the equator, on the other hand, all stars rise and set each night.

To a good approximation, over time–scales of a century or two, the Earth's rotational axis always points in the same direction in space. The rotational axis is tilted relative to the orbital axis by a constant 23°, this means that the noontime sun appears to bob up and down as the year goes by. Returning to Melbourne and advancing our simulation of the sky a month at a time, we can see this effect. When the noontime sun is highest in the sky it is the time of the summer equinox and the start of summer. Likewise when the noontime sun is lowest in the sky it is the winter equinox and the start of winter. In our simulations the sun is not exactly at the highest point in the sky at noon since Melbourne does not lie exactly at the centre of our time zone. The celestial equator is the projection of the Earth's equator on the sky. The sun lies on the celestial equator at noon twice each year at the equinoxes.

The pole star was an invaluable navigation aid to early navigators. Before the invention of accurate clocks and the arrival of the magnetic compass from China, it was always possible to measure your latitude by measurement of the height of the pole star above the horizon. As ships sailed south down the west coast of Africa from Europe, the sailors were in serious trouble when the pole star dipped below the horizon!

Over long periods of time, the direction of the Earth's spin axis changes. Eventually, the pole star will appear to drift away from its privileged position directly above the North Pole. The shift in the direction of the Earth's spin axis is a result of precession, the same effect seen when a spinning top wobbles when gravity tries to topple it over. This precession is a direct consequence of the vector nature of angular momentum. Spinning objects 'like' to maintain their orientation in space and attempts to tip them over do not succeed, the spinning object precesses instead.

The precession of the Earth is caused by the gravitational pull of the Moon, and a lesser

Torque on the Earth from the gravity of the Sun and Moon causes the Earth's spin axis to precess. From Zelik and Smith.

extent the Sun. This gravitational pull acts on the equatorial bulge of the Earth which is in a plane tilted, on average, 23° to the plane of the Moon's orbit. The pull on the equatorial bulge produces a torque on the Earth which would have the effect of straightening up the Earth if it was not spinning.

The rate of precession of a spinning object is inversely proportional to the moment of inertial and the spin angular frequency. For the Earth, these are big numbers! Hence the Earth precesses very slowly, taking over 26,000 years for the spin axis to precess around one circuit. During this time Polaris will drift off the celestial axis, to be replaced, in 14,100 AD by the star Vega. We can see the effect of the precession by running the time in our simulated view of the sky backwards, stopping every millennium to look at the sky, as the celestial axis makes its slow circuit in the sky. We shall stop at around the year 12,200 BC when Vega was last the pole star.

Let us take a closer look at the sky of this distant time. Passage of the seasons was very important to the Stone Age people of the time, the coming of Spring was anticipated each year by observation of the constellation that rose with the dawn at the Spring equinox, signaling the end of Winter. In 12,200 BC, we see that constellation was Taurus, the bull. The eye of the bull is the first magnitude bright star, Aldebaran. For the next 4000 years, the eye of the bull rose just before the spring dawn. But the precession of the Earth's spin axis causes Taurus to slip behind the Spring dawn, by around 8000 BC even Aldebaran would be so low as to be invisible in the glare of dawn. Some scholars have calculated that Aldebaran could have faded from view in no more than two hundred years. It is possible that this event could have had a profound effect on people with sufficiently long cultural traditions.

By the time of Galileo, evidence for the heliocentric model of the solar system had become overwhelming. Observations of the phases of Venus and variations in its angular size, the moons of Jupiter and the keeping of careful records of the positions of the stars and planets led to an increasingly detailed understanding of the structure of the solar system. Drawing on all this information, Isaac Newton was able to formulate his theory of gravity.

Gravity.

The shape of our solar system is determined by gravity. You already know that the Earth rotates around the Sun and that the Moon rotates around the Earth, but it is also true that the Earth rotates around the Moon! Since the Moon is much lighter than the Earth, the orbit of the Earth has a very small radius. In fact the radius of this orbit is smaller than the diameter of the Earth. Both the Earth and the Moon orbit around what is called the barycentre of the Earth/Moon system. This point lies 1400 km beneath the surface of the Earth. Therefore, seen from outer space, the Earth appears to swing from side to side as it orbits the Sun. This side to side motion has also been looked for in stars. If seen, it would provide evidence for the existence of heavy planets in orbit around those stars.

An asteroid ejected from the solar system by Jupiter seen from the Sun (left) and Jupiter (right). From 'Gravity'.

The structure of the solar system is determined not only by the gravitational interaction between the Sun and the orbiting planets, but also between the planets themselves. The biggest planet, Jupiter, exerts the strongest influence. In fact Jupiter prevents some possible orbits around the sun from being occupied by any planet. In an orbital simulation, we can see an asteroid orbiting closer to the Sun than Jupiter in a carefully chosen orbit which is stable, but an asteroid orbiting further out gets dragged from its orbit and eventually thrown out of the Solar System completely! It is interesting to look at this situation again from the vantage point of Jupiter. In this case, both the inner and outer asteroid display 'retrograde motion' and appear to loop backwards in the sky. This occurs for the inner asteroid whenever it swings behind the sun. It occurs for the outer asteroid as Jupiter overtakes it in Jupiter's faster orbit. The outer asteroid eventually passes too close to Jupiter and is ejected from the Solar System by the 'slingshot' effect.

The slingshot effect was exploited by the *Voyager* spacecraft to speed them on their way to the outer planets. The effect is often described as a 'non–impact elastic collision' since the light asteroid, or spacecraft, approaches a heavy planet in a near head–on collision trajectory. The two objects interact via gravity and the lighter asteroid or spacecraft is 'bounced off' (actually makes a close hyperbolic orbit) and is sent back the way it came with its original speed, plus twice the orbital speed of the heavy planet. This is a direct consequence of the fact that the relative speed of the two objects involved in the collision is the same before and after the collision.

Not only does gravity determine the structure of the Solar System, it also determines how much atmosphere a planet is able to hang onto. Warm gas consists of fast moving molecules that bounce of each other and the surface of the planet. Some rise high above the

The distribution of gas molecules in a gravitational field. From ‘Teddy’.

surface before gravity pulls them back. If the temperature is high enough, the high flying gas molecules may have enough speed to escape from the planet entirely! This is why the Earth’s Moon has no atmosphere and Mars has very little, the normal temperature of these relatively small bodies is high enough for the fast gas molecules to leak out into space. For the same reason, Earth could never have an atmosphere of the light gas hydrogen. At normal temperatures, the hydrogen moves too fast to be held by Earth’s gravity.

The Home Solar System.

Having taken a look at the Solar System and the Celestial sphere from the surface of the Earth, and looked at some of the effects of gravity, we can now skip lightly over all the hard work that went into working out a successful model for the solar system and take a look at the whole works from the outside.

Recently, for the first time in history, it was possible to obtain an actual image of the solar system as it appears from outside. This image was obtained by the cameras on the *Voyager 2* spacecraft. This was the cameras’ final job before they were shut down as the spacecraft plunged outward into interstellar space. From 40 A.U. (1 A.U. is equal to the radius of the Earth’s orbit which is about one hundred and fifty million kilometres) it is just possible to make out Venus, Earth, Jupiter, Saturn, Uranus and Neptune. The rest of the Solar System is too dim to be seen. This shows how difficult it is to find a good vantage point to get an overall view of whole solar system. The scale is simply too great, the objects in it are too small and dim.

Fortunately, with a sophisticated model stored in a PC, we can zoom around at will viewing the sights up close. From a ‘starship’ vantage point of a distance of 3 light days (about 520 A.U., thirteen times as far as *Voyager 2*), the whole shape of the volume of space occupied by the planets of our solar system is evident.

What is most obvious about the starship view is that most of the planets orbit close to one plane, in fact within 3.4°, with the exception of Mercury (7.0°) and Pluto whose orbit is inclined by a massive 17°. This near planar configuration is a result of the way the Solar System formed from the collapse, due to gravity, of the original protosolar gas cloud. As the cloud collapsed, it always retained angular momentum which prevented the cloud from collapsing into a point but produced a rotating disk instead. Pluto's peculiar behaviour is thought to be because it was once a moon of Neptune. Early in the history of the solar system, gravitational perturbations from the rest of the solar system wrested Pluto from Neptune and let it escape to follow its own orbit. Indeed, the orbit of Pluto crosses inside the orbit of Neptune, where Pluto can be found at the moment. This can easily be seen by viewing the solar system from a point directly north of the Sun.

This view also reveals the congested scale of the inner solar system. The scale of the Solar System dramatically decreases upon moving to the inner solar system. The scale of the Solar System goes roughly as a power series known as the Titius–Bode Law, first formulated in 1766. The physical basis of this empirical law remains controversial. The law does not successfully predict the orbit of Neptune, or, of course, Pluto. However, there is some evidence that many of the 'native' moons of the outer planets are also located according to a modified version of the Titius–Bode law, which may suggest an underlying physical phenomenon governs the formation of planetary, and satellite, systems. A 'native' moon is one that formed along with the parent planet out of the protosolar cloud. We shall see some examples shortly.

Our view of the inner Solar System reveals the relatively eccentric orbit of Mars. This has severe implications for large seasonal changes on Mars! In our model we also see the relatively fast pace of the inner planets in their orbits. Since they orbit close to the Sun, where gravity is strong, they need to travel fast to avoid being pulled in to the Sun.

(Left) Retrograde motion of Mars seen as Earth overtakes it in its orbit. (Right) Mars with its two moons drawn to scale. Images from 'Dance'.

The outer planets move ponderously in their orbits compared to the Earth. This means that we are continually catching up with them and overtaking them in our relatively fast orbit. As we saw earlier, when overtaking an outer planet, it appears to begin to move backwards in the sky for a short time, before resumption of its forward motion, when seen against the backdrop of the 'fixed stars'. In our simulation we look at the sky at intervals of on sidereal day (a single rotation of the Earth relative to the stars) so that the stars appear to stay fixed in the sky. We can see Mars execute a peculiar retrograde loop in the sky. This was a real headache to explain in the early geocentric theories of the solar system, but is very straightforward with the heliocentric model.

A very large gap is noticeable between the orbit of Mars and Jupiter. Since the radii of the orbits of the planets seemed to follow the simple empirical Titius–Bode law, a planet was long predicted to inhabit this gap before the first asteroid was discovered in a position roughly predicted by the law. The asteroids are now thought to be the remnants of early solar system material that was prevented from accreting into a planet because of the disruptive effects of Jupiter's gravity. It is estimated that there are over one hundred thousand asteroids larger than one kilometre in diameter, but their combined mass is estimated to be around one twentieth that of the Moon. They orbit in a huge toroidal shaped volume of space, and their orbits are ruled by the gravity of Jupiter, as we have seen. Significant numbers of asteroids are found inside the orbit of Mars.

Just as Jupiter can create regions of instability in the asteroid belt, it can also create 'safe havens' where asteroids can orbit unmolested. Two such safe havens are shown in a plot of all known asteroids. These safe havens are formed by the combined effects of the gravitational field of Jupiter and the Sun and are known as the Lagrange points after Louis Lagrange (1736–1813) who first predicted their existence. One point lies 60° ahead of Jupiter in its orbit and the other lies 60° behind. Asteroids inhabiting these stable points are known as Trojan asteroids.

We can use the computer model to take a closer look at the planets and their systems of moons. Let us start with the Earth. It is a remarkable fact that both the Moon and Sun appear to be close to the same size in our sky. The Sun subtends an angle of 0.53° compared to the Moon which varies between 0.49° and 0.55° depending on its position on its elliptical orbit. This means that it is possible for the Moon to completely block the Sun in a Solar eclipse.

When the Sun is shaded by the Moon in a solar eclipse, it is possible to see the Sun's corona. Image from 'Dance'.

Last year there was a Solar eclipse, visible from Hawaii and Central America. In our simulation, we see a new Moon pass across the face of the Sun. At totality, the Solar corona, or atmosphere, is visible as it is no longer hidden by the glare from the much brighter Sun's disk.

There was also an eclipse of the Sun last year visible from Australia. In this case the

Moon was further from the Earth and was not large enough to completely cover the Sun. In our simulation, seen from the vicinity of Hobart, we see a bright annulus of sunlight surrounding the black disk of the Moon.

In a Lunar eclipse, the Moon passes into the Earth's shadow. In this case we can see details of the structure of the Earth's shadow on the Moon. Earth's shadow comprises a dark central core, called the umbra, surrounded by a less dark annulus called the penumbra. This is because the Sun is not a point source and so does not cast a perfectly sharp shadow. On top of all this, refraction of the Sun light through the Earth's atmosphere gives objects in the Earth's shadow a ruddy glow. The curved shape of the shadow of the Earth on the Moon provided observers with the first evidence that the Earth was a sphere.

A famous lunar eclipse in history is perhaps described in the Bible during the time of the crucifixion. On April 3, 33 AD, at about 5 pm (near sunset), a partial Lunar eclipse was visible from Jerusalem. This would have made the Moon appear blood red, a terrible sight to those caught up in the events below.

Moving out from the Earth, we encounter Mars and its two tiny moons. Mars, the planet most like the Earth, was too small to hang onto a thick atmosphere and by now, 4.5 billion years after the Solar System condensed out of the protosolar cloud, most of it has leaked away into space. Because of the proximity of Mars to the asteroid belt, it is thought that the two moons are both captured asteroids, although the precise capture mechanism is not clear since the low mass of Mars makes capture events unlikely. Until the Galileo spacecraft encountered asteroid Gaspra on the way to Jupiter in October last year, images of Phobos and Demios were taken as representative of real asteroids. Indeed, the images of Gaspra look exactly like those of the moons of Mars.

Beyond the asteroid belt, Jupiter orbits with its host of moons. At last count there were over 16. Some of these are no doubt temporary captures from the asteroid belt. Our simulation shows the image of Jupiter as seen by Galileo (the scientist, not the spacecraft!) in 1610. Galileo's homemade telescope was sufficient to clearly resolve the four largest moons: Io, Europa, Ganymede and Callisto. These orbit rapidly around Jupiter as our simulation shows, noticeably changing position in just a few hours.

In Galileo's meticulously kept logbook, he recorded the position of stars he saw drift across the field of view of his telescope as Jupiter changed its position in its orbit. One such 'star' cannot be found on any star chart. Looking at a simulation of the nights around when Galileo was making his observations shows why. The 'star' was in fact the planet Neptune! Galileo had unknowingly discovered Neptune 234 years before its official discovery in 1846. Careful calculations of the position of Neptune on the nights when Galileo saw it are at odds with the, believed reliable, positions in his logbook. It is not clear where the error comes from. A possible, but improbable, explanation is that an additional planet remains to be discovered out beyond Pluto. This is improbable because many careful searches have failed to find any additional planets of our Solar System.

A quick look at Saturn reveals its beautiful ring system. This is a feature now known to be shared by all the giant gas planets, although Saturn's rings contain the most material and are the most spectacular. Beyond Saturn lies Uranus, a most peculiar planet. Uranus rolls along its orbit, at the moment its north pole points directly at the Sun! Our simulation shows the backlit planet, allowing its dark ring system to be seen. We see that the rings and the moons all orbit in a plane at right angles to the rest of the Solar System. It has been proposed that a violent collision tipped the proto–Uranus on its side while it was condensing, early in the history of the Solar System. Enigmatically, the magnetic field of Uranus, discovered by *Voyager 2*, points roughly up and down, just like the other planets! After a quick look at Neptune on the frontier of the Solar System, we move out to another star.

Double Star Systems

Most stars near the Sun exist as multiple star systems. The proportion could be as high as 80 %. Therefore, most of the apparently single stars seen by the naked eye can be resolved into binary, or more, systems with a telescope. Other systems are too remote, or too close together, and their structure has to be deduced indirectly.

An example of an indirect method of finding a double star system is shown the the Algol eclipsing binary star system. This system in in the constellation of Perseus. It was discovered to be a binary by observation of its brightness fluctuations over the 70 hours it took the two stars to rotate once around each other.

Our simulation shows the binary to consist of a bright star and a dim star rotating in a plane almost parallel to our line of sight. When the dim star eclipses the bright star, the intensity of the system decreases significantly. Additional small fluctuations in intensity can be accounted for by assuming the bright star produces a hot spot on the dim star. This hot spot, on the side nearest the bright star, is only visible just before and just after the dim star goes behind the bright star.

The eclipsing binary star system of Algol. From 'Starcrossed'.

We can also use our gravitational simulator to model possible planetary orbits around double star systems. Many possible orbits are unstable and result in the planets crashing into one of the stars. In one of the simulations we see two planets in orbit around a double star system. The orbits never repeat the same path, working out a calendar on these planets would be a problem! The planets are doomed to disaster, both end up colliding with a star.

Imaging the Sky

Having had a close look at the virtual sky in the computer, we can now turn to look at the real thing. Recently, advances in technology have drastically reduced the price of Charge Coupled Devices (CCD) allowing their widespread deployment outside of professional astronomy laboratories. These devices consist of an array of tiny light sensors that convert incoming light photons into electric charge. Each sensor contributes one pixel to the image. The electric charge accumulates in the device allowing long exposures to be made of dim objects. At the conclusion of the exposure, the accumulated charge in each sensor is read out into a computer where it is converted into an image.

Considerably greater sensitivity than photographic film is possible. This is because photographic film only responds to 2–3 % of the photons which fall on it, compared to 40–80 % on a CCD. Also CCD sensors do not suffer from over exposure or reciprocity failure like film. Since the image from a CCD array is available in digital form, a whole host of numerical image processing techniques can be used to highlight faint and subtle details.

Computer enhanced CCD images of galaxies. From the Buil–Thouvenot CCD atlas of Deep–Sky Objects.

CCD images of galaxies, software enhanced In an image of the Horsehead nebula, captured by a CCD array, we can see some interesting details of this nebula of dark gas which intrudes into a bright strip of photo–ionized hydrogen. Image processing allows us to see faint details of the dark cloud.

Many of the images reveal evidence for collisions between galaxies, an apparently common event in the Universe. Even something as majestic as this can be modeled on the screen of a PC. Our simulation shows a greatly simplified model for the near miss collision between a small and large galaxy. Despite the simplicity of the model, the results look very much like those done on high powered CRAY supercomputers, or indeed the real thing!

Although the computer simulations shown here have been refined to a high degree of sophistication, any computer model must only remain an approximation to the real thing.

For example, our simulations of the sky of Earth over long time periods did not take into consideration the proper motion of the stars as they orbit the centre of our galaxy. This effect drastically changes the appearance of the constellations, given sufficient time. Despite these limitations, computer simulations can significantly enhance our understanding of the complicated Cosmos that surrounds us.

Computer software used in this lecture:

* Indicates software available on a companion diskette.

'Dance of the Planets', Version 2.5, by ARC Science Simulations Software Inc., P.O. Box 1955, Loveland CO 80539, USA. An unusually complete simulation of the entire solar system, with a comprehensive backdrop of stars, galaxies and other deep sky objects.

* 'Dance of the Planets Sampler', Version 2.5, ibid. A guided tour of a subset of the complete program.

* 'Skyglobe', Version 3.1, by M.A. Haney, KlassM SoftWare, 284 142nd Ave., Caledonia MI 49316, USA. A planetarium simulation of the stars and planets.

* 'Moons of Jupiter Orbital Clock', Version 0.00, by A. Jones, Eagle Rock Village 4–6B, Budd Lake NJ 07828, USA. A guide to the appearance of Jupiter and its Galilean moons.

* 'Gravity', Version 2.0, by S. Safarick, P.O. Box 45072, Seattle WA 98145–0072, USA. A simulation of the way objects move under the influence of gravity.

'Starcrossed', Version 1991, by J.R. Naiden, Zephyr Services, 1900 Murray Ave., Pittsburgh PA 15217, USA. A variety of simulations of multiple star systems.

'Galaxcrash', Plus version, copyright 1991, Zephyr Services, ibid. A simple, but effective, simulation of colliding galaxies.

'BT-show', the Buil–Thouvenot CCD Atlas of Deep–Sky Objects, software by R. Szczepaniak, CCD images by C. Buil and E Thouvenot, 1991, Sky Publishing Corporation, P.O. Box 9111, Belmont MA 02178–9111, USA. A spectacular collection of CCD images, available as a sample of the complete library (1 disk) or the complete library itself (20 disks).

'CCD', 'CCDUTIL' and 'CCDBLINK', for the ST–4 Star Tracker Imaging CCD camera from Santa Barbara Instruments Group, 1482 East Valley Rd., Suite 601, Santa Barbara CA 93108, USA. Image collection and processing software.

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