



Current Notes

The Journal of the Manchester Astronomical Society
May 2009

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LIBRARY NEWS

The following purchased books have been added to the library:

Just Six Numbers by Martin Rees, published by Weidenfeld & Nicolsen, London, 1999.

If you have ever wondered how a single event could generate all the matter contained within the Universe or asked yourself 'what are the fundamental laws that govern our Universe?' then this book is for you.

Some of you might remember Guy Duckworth's talk on the six numbers that represent the deep forces that shape the Universe. This book was the basis for his talk.

The Goldilocks Enigma by Paul Davies, published by Penguin Science, 2007.

The front cover of this book asks the question "Why is the Universe just right for life?". This book very much compliments that written by Martin Rees but approaches the subject in a different way. The field of cosmology can be very daunting but Davies' style makes the book very readable. A good introduction to cosmology.

LIFE in Space, edited by Robert Grant Mason, published by Time-Life Inc, 1983.

Some people would describe this as a 'coffee table' book. It is large format and the pages abound with mainly coloured photographs. There are only six chapters - Mercury, Gemini, Apollo, Skylab, Space Shuttle and Deep Space. All the missions are well illustrated with meaningful captions and good introductory text. Perhaps a book to browse rather than to read from cover to cover. Published over 26 years ago this is an account of the early pioneers of space travel and should serve well to those members who wish to research this period of space exploration.

Three books have also been donated by Cliff Meredith:

Atlas of the Skies published by TAJ Books, 2003.

Subtitled '*Journeying between the Stars & Planets in the Discovery of the Universe*'. A book aimed at would be astronomers. A simple and well laid out book.

The New Solar System Ed by J. Kelly Beatty and A. Chaikin, published by Cambridge University Press, 1990.

Although the information is now 20 years old this book is still a fascinating read for those members who are interested in our solar system rather than deep sky.

Images of each Universe, Ed by Carole Stott, published by Cambridge University Press, 1991.

Those expecting a 'coffee table book' with lavish photographs will be disappointed. This is yet another overview of the Universe in 15 Chapters each of which is written by a different author.

VISITS TO THE GODLEE

5th January 2009 - The Victorian Society, Manchester Branch.

26 guests were given a tour of the Observatory by Tony Cross, Kevin Kilburn and myself. Kevin also gave a brief talk on the history of the Society. We also provided light refreshments.

7th January - SPICE (Manchester) - The UK's largest Multi-Activity Adventure, Sports and Social Group.
(<http://www.spicemcr.com/index.asp>)

27 guests were given a tour of the Godlee by Tony Cross, Anthony Jennings, Marion Mills and myself. This was followed by a short talk by Anthony about the MAS and its activities.

2nd March - Flickr Photographic Group (Manchester).

11 members of Flickr.com, a photographic website, visited the Godlee Observatory. The visit was arranged by Tony Cross following a fortuitous meeting with a group of people in Albert Square who were busy photographing everyone and everything.

The visit to the Godlee was hosted by Tony Cross, Anthony Jennings and myself. Time was allowed for our guests to visit the upper floor where Tony gave a brief history of the MAS and the Observatory.

A large number of photographs were taken of the telescope and views of the Manchester skyline were taken through the open dome. Many photographs were also taken in the octagon room with the spiral staircase being of particular interest. Anthony then presented a slide show illustrating some of the work carried out by MAS members. This was followed by a live demonstration on how to take 3-D photographs and some examples that can be achieved simply by using your digital camera, a piece of software called Anaglyph Maker and a little practice.

A record of the initial meeting and many of the photographs taken on the night can be found on the Flickr website
www.flickr.com/search/?q=Manchester+Astronomical+Society and
www.flickr.com/search/?q=Godlee&m=text.

Alternatively go to www.flickr.com and search for Manchester Astronomical Society or Godlee.

AGM 2009

The Manchester Astronomical Society Minutes of the Annual General Meeting held on the 16 April 2009 has been posted on our notice board. Any member who is unable to attend the Godlee can request a copy which will be sent with the next issue of 'Current Notes'.

The Officers for the 2009/10 are as follows:

President: Barry Henshall
Vice President: Guy Duckworth
Secretary: Michael Oates
Treasurer: Anthony Jennings
Publicity Officer: Tony Cross
Immediate Past President: Graham Hodson

Council Members: David Shakeshaft
Kevin Kilburn
- *Vacant* -
- *Vacant* -

Non-elected posts fulfilled by Council members

Editor of Current Notes: - *Vacant* -
Librarian: Barry Henshall
Safety Officer: Michael Oates
Public Lecture Organiser: Kevin Kilburn
Membership Secretary: David Shakeshaft

See the final page for contact details.

CURRENT NOTES

Andrew Fearnside has published Current Notes for a number of years but has now decided to step down from this post. Andrew has produced a quality publication under his editorship and I am sure members have appreciated the hard work that goes into every issue. As you can see from the above list of Officers the non-elected post of Editor of Current Notes is now vacant. I feel that it important to maintain publication, not only as a way of communicating with those members who are unable to attend the Godlee but also as a record of member's activities. As a temporary measure I have gathered together a number of items of news and members contributions. Thank you to all who have responded with copy.

Anyone who feels they could take on the editorship will be welcomed with open arms. The post requires collecting articles etc, typesetting (Microsoft Word[®]), and printing. It need not be the responsibility of one person. The work can be shared.

NORTH WEST GROUP OF ASTRONOMICAL SOCIETIES (NWGAS)

On Saturday 25th April 2009 Kevin Kilburn and myself attended the NWGAS AGM hosted by South Cheshire AS at Ravensmoor Methodist Church Hall. The minutes are posted on our notice board but 2 items perhaps should be highlighted.

Any member who feels they can give a talk/presentation to other Societies within the northwest should, in the first instance, contact Kevin or myself.

There was also discussion about the possible development of 'Expert' workshops to enable interested NWGAS members to learn advanced skill in areas such as astro image capture and processing. Details have been posted on our notice board but if you wish details to be e-mailed then please let me know. Please let me know before the end of June if you are interested so that I can put your name forward.

Barry Henshall, President

MAS WEBSITE

Because many members are in the habit of e-mailing images to each other with "what do you think of these" in mind, and I am often included in these exchanges, it is difficult to decide which (if any) are intended for publication on the MAS website.

Therefore, may I please ask:

If you have an image/s that you would like included on the MAS website to send it (them) to website@manastro.co.uk

Please include any "technical" information (e.g. number of frames stacked, exposure times, etc) with your e-mail, if not included on the actual image.

Any images sent to any of the other of my or the MAS e-mail addresses will not be placed on the website.

Graham Hodson

Use of a D-SLR to Image the Deep Sky for Urban Astronomers

A thousand stars can be seen by naked eye from a dark location, but light polluted inner city observers may be lucky to see a hundred. Living 4 miles north of Manchester City Centre I might see 300 stars on a good night (limiting mag +4.3). Astronomical observing using naked eye, binoculars or a telescope can be a wonderful experience, but trying to see faint Deep Sky fuzzies can be frustrating. Light pollution restricts some observers to viewing the Moon and planets. However, recent advances in digital/electronic imaging now enables amateur astronomers to produce results that would have amazed professionals using big observatories only three decades ago.

Modest digital photographic cameras (even on mobile 'phones) can be used for a variety of astro imaging. Webcams are excellent for lunar and planetary imaging A D-SLR (Digital-Single Lens Reflex) cameras is able to produce fine colour images of Deep Sky Objects (D.S.O).

For astronomy, as many things, it can be a matter of "horses for courses. For anyone wanting to do serious scientific astronomy specialist CCD equipment is probably still best. However D-SLRs can be used stand alone (i.e., you do not need use of a PC for image capturing) and so can also be used for ordinary landscape/portrait pictures as well).

D-SLRs employ detachable lenses enabling a variety of different optics, fixed or zoom photographic lenses and telescopes to be used.

I will now outline an observing/imaging session using a D-SLR and modest sized telescope to get two quite different astronomical objects on a single image.

Equipment

HEQ5 Pro mount, including tripod (this is the heaviest I can manhandle, some experts say the HEQ5 Pro is about the lowest priced, minimum specification recommended for Deep Sky imaging). Weight 11.5 kg.

William Optics 88 mm f5.6 APO refractor Weight 7 kg, (compact and very

manageable).

2 inch Star Diagonal, T-ring camera adaptor and 2 inch extension tube.

2 inch light pollution filter.

Canon 300D lightweight 1.0 kg (Entry Level D SLR now obsolete\superseded but still reasonable specification for astro imaging).

P.C. Computer/XP operating System.

Note: D-SLRs use memory cards so a PC is not essential for image taking, but is needed for image processing and has other uses.

U.S.B. cable plus two 5 metre extensions and booster.

Software (Canon camera software, Deep Sky Stacker and Paint Shop Pro).

Setting up procedure

(1 hour and 0.7 hours dismantling and storing). Not having an observatory, I set up my HEQ5 Pro in the garden (in daylight), adjacent to the kitchen, allowing access to a transformed 12 volt electric power and an indoor computer using long cables through open windows. The tripod is positioned viewing a neighbours house corner (above which Polaris appears). Power supply, long USB and Go To Handset cables are connected. The W.O. refractor is clamped on the HEQ5 and a star diagonal and eyepiece fitted.

After checking everything is okay power is turned on. The appropriate HEQ5 RA circle's date, time and polar scope are then adjusted and aligned on Polaris when the sky is dark enough.

The next procedures to be followed are indicated on the HEQ5 handset's illuminated display (i.e. need to input latitude, longitude, date, time and finishing with a 3 star alignment). At this stage each of the appropriate alignment stars need to be observed through the main telescope and each star centralised in a suitable eyepiece (preferably one with crosshairs and fitted to the scope via a star diagonal).

When all is done satisfactorily the handset

readout displays "Alignment Successful".

Note - I had previously used a standard Now Go To HEQ5 for several years before upgrading to the Pro. The Pro's Go To enables faint D.S.Os to be readily located without neckcracking and grovelling on cold ground.

Observing

Except for the camera, the equipment is ready for action. However, newcomers are advised to do some visual observing to get familiar with any quirks before trying to image. By using the HEQ5 Pro's handset built in "Guided Tour" observers can readily enjoy views of some nice celestial lollipops as the telescope automatically Go Tos to chosen objects. If no wonderful splendours are revealed the equipment probably needs setting up again – properly!

Imaging

To organise the camera I fit a fully charged battery, remove the 18-55 kit lens from the Canon 300D and replace it with a T-ring (EOS fitting) attached to a 2 inch adaptor tube with light pollution filter). I set the 300D to manual mode, 30 seconds exposure and 1600 ISO (a lower ISO would probably produce less noisy images, but requires longer exposures). The eyepiece and star diagonal are taken off the refractor's focuser. The USB cable is connected to the 300D, I wrap the camera strap around the telescope tube (to ensure the camera will not hit the ground if it happens to fall off), then slide the camera adaptor tube into the Crayford focuser and tighten up the appropriate set screw).

The 3rd alignment star now being visible in the cameras view finger the refractor is tweaked to better focus. However, the viewfinder is small and focusing tricky. This is where the PC is very useful. I then switch on the 300D, nip indoors, connect the long USB cable to the PC, fire up Canon's "Remote Capture" software, then use the computer mouse to shoot an image with the 300D.

There follows a finicky period nipping out and indoors several times to re-focus image, view images and achieve best focus. Downloading just one image and

adjusting focus can taken about 3 minutes but viewing the large PC monitor image is better than squinting at a camera viewfinder (or even small "Live View" LCDs on more modern D-SLRs).

Tackling Faint Fuzzies

Purists may want to locate their quarry by sportingly star-hopping but I am usually happy to use my HEQ5 Pro's Go To. So a few moments after punching instructions into the handset the refractor automatically slews to my target.

Incidentally, my W.O. 88 mm f5.6 refractor produces quite wide fields of views so a separate finder scope is rarely needed. My 300D refractor images a 3x2 degree field which is not demanding of the HEQ5 mount and drives, though perhaps rather large for imaging many D.S.Os in fine detail, but excellent for bigger objects, or capturing more than one object at once if close together.

I chose to image Messier 108 for several reasons :

- a) It is a fine edge on SB spiral galaxy
- b) As fuzzies go it is quite bright Mag +10, 8'x2'
- c) The splendid "Owl" planetary nebula M97, 3', Mag +9.9 is only a degree from M108, providing a nice second and very different sort of object on the same 300D image.
- d) M108 and M97 are in Ursa Major and well placed overhead at the time for observing/imaging.

I then took a few 30 second shots to make sure stars were focused and M97, M108 nicely positioned on images.

Previously I had done most 300D imaging using Canon's "Remote Capture", easy to use, but limiting me to a maximum 30 second exposures. However, I had recently made a 12 metre cable enabling me to extend my 0.6 metre standard Canon cable release so I can use the Canon's "Bulb" to shoot long 300D exposures whilst I sit warm indoors.

The new technique has some important advantages over Remote Capture, but a few drawbacks as well.

I then abandoned my P.C. and began

imaging M108 - M97 in earnest using the long 300D cable release. Being a decent night (at least good to start with !) and my target well placed, above the worst light pollution, I kept the 300D setting 1600D and decided to take 90 second exposures, taking as many exposures as possible (i.e. until I got fed up !).

I clicked away in oblivion nervously using my new technique (at least new to me). Having no automatic timer I used an accurate radio clock to make 90 second exposures allowing 30 seconds before clicking the next. In effect each image took 2 minutes to get, so I could capture a 90 second shot almost as quickly as a 30 second shot using Remote Capture.

However, I was well aware of at least one snag to my new technique. Using Remote Capture I see every image on the PC Monitor a minute after taking them. My new method kept me in the dark.

Beforehand I had decided to stop imaging from time to time to check my images were okay and downloaded on the memory card properly. In the event after an initial check I merrily clicked away sitting in the warm kitchen intent on getting 40 images before reviewing things.

40 stacked 90 seconds images roughly equates to a single One Hour exposure, which would be a new record for me, my previous "best" being 80x30 seconds = 40 minutes.

However, having taken 39 and feeling quite pleased that I was about to well and truly break my own old "World Record !", I glimpsed some cloud through the window.

When I checked outside properly - horror of horrors ! Cloud was covering most of the sky. I soon discovered that 21 of my supposed 39 images were useless. Having got over my initial shock I realised it could have been worse my decent 18 No. 90 second exposures equate to 27 minutes.

I ended the imaging session by taking some so-called "Darks" i.e., covering the telescope aperture and taking dark exposures each of 90 seconds the same exposures time as the actual main images. I also took some "Flats", images of a pure white card illuminated, using exposure

times that produce results whereby the Histogram spike is midway across the graph.

My imaging session was thus completed, not perfectly, indeed somewhat prematurely, but to some relief reasonably successfully. My useful 18 images took about 40 minutes to capture, but I had spent as long again hoping to get another 22 that turned out duff.

Getting the Darks and Flats took another quarter hour. All told from starting setting up to finishing storing my equipment, the session took about 3.5 hours.

Next day, being retired, I spent a leisurely half day image processing my cherished images on the PC. All my 18 useable 90 second M108/M97 images, the Darks and the Flats were changed from their original RAW captured format to TIF using Canon 300D computer software. My resultant TIFs were then processed using "Deep Sky Stacker" (DSS) software.

NOTE: the most recent version of DSS enables RAW image files to be stacked. This both supposedly improves the final processed image quality and speeds up processing.

Doing the DSS image processing, including creating the TIFs, took about 2 hours (most of that time the P.C. was left alone running doing it's own thing). However, I do like to be at the P.C. when the final DSS processed image appears on the monitor screen.

Unaware newbies may sometimes find their initial stacked DSS result appears somewhat disappointing. In fact DSS does have a few more tricks to improve the stacked results appearance, but I personally save the initial result as a TIF and transfer that to the final image processing software. I use Paint Shop Pro (PSP).

The downloaded resultant DSS TIF when displayed in Paint Shop Pro usually looks quite good immediately. However, using some PSP processing techniques judiciously, such as careful simple brightness/contrast stretching, gamma stretching and curves, makes things better.

So it was with my M108/M97 image.
However, the result is never a totally
guaranteed successful conclusion, which

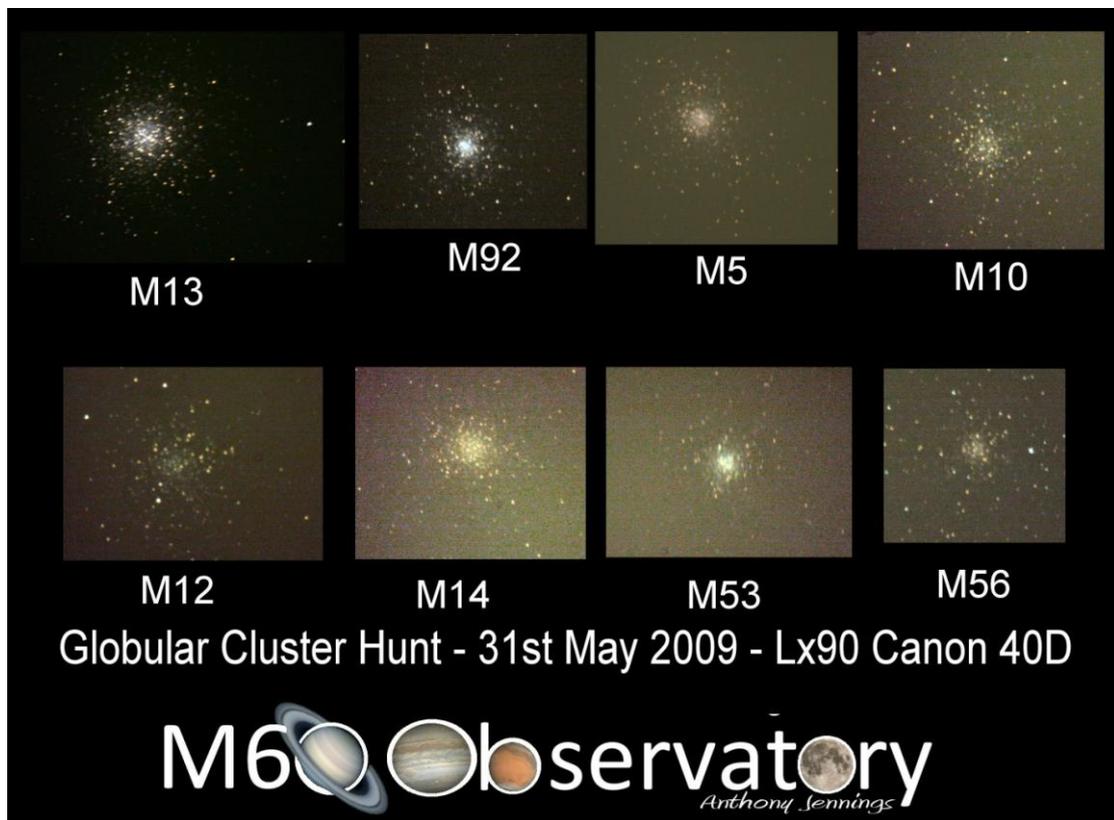
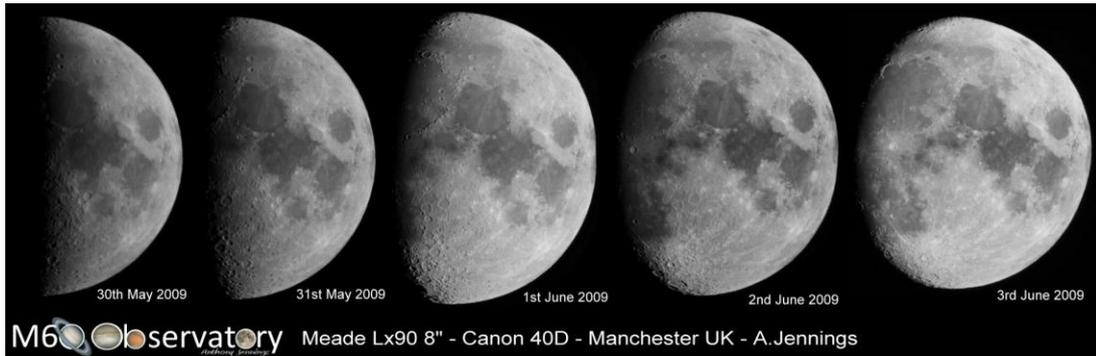
is all part of the fun of imaging !



My original 88 mm f 5.6 refractor - Canon 300D-SLR combination provided an image field of 3 x 2 degrees. I have cropped the image such that the field is only about 1.5 degrees wide to make M97 and M108 look bigger.

Cliff Meredith 9 May 2009.

PICTURE GALLERY



Guy Duckworth gave a presentation for June Skynotes on Globular Clusters , I thought 'I wonder how many I could image in one night.'
Having fine tuned my alignment and collimation of my Meade Lx90 I programmed my Autostar to seek out Globulars. Using my modified Canon 40D attached to the back of my telescope I imaged a total of 8 Globulars. Using setting circles to find the objects would have taken far longer than the Autostar. Thus enabling to have a successful evening.

PICTURE GALLERY



Image is a stack of 54x30sec pix at ISO800 on the Canon 350D with the 300mm Pentacon stopped to f5.6. Sequence began at 2345UT, 24th May, and lasted for about half an hour. MUCH skyglow cropped out in the wider view and the box around Pluto was then selectively auto-levelled to show the planet more clearly.



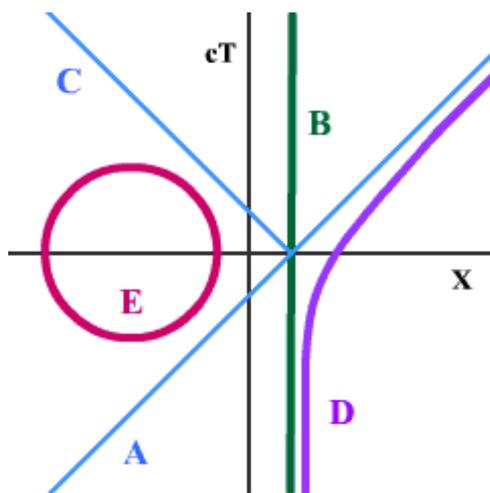
Dumbell Nebula - M27, NGC 6853, LX90, Canon 40D -
single shot (normally ISO 1600 - 30secs) - Anthony Jennings
(Enhanced by Kevin Kilburn)

Warp Factor Two

Causality, Gravity & Einstein's General Theory of Relativity

Technically, we're all travelling in time just by existing. But we can't seem to control our motion through time in the same way we can control our motion through space. What most people usually mean by time travel is the ability to move around in time the same way they'd move around in a city.

So what do we mean by Time Travel? Let's look at a space-time diagram that shows a few examples of different ways observers or objects can travel in time and space:



It's important to remember that any single point on this diagram represents an event - both a moment in time and a location in space. The origin of the axes in the figure represents the place $X=0$ at the time $T=0$. This is what we mean by a space-time event. The figure is a space-time diagram showing space-time paths of various observers moving in 1+1 dimensional space-time. Paths A, B, C and D represent the normal kind of time travel that we find in our world. Path E shows an example of a kind of time travel that is not allowed in Special Relativity.

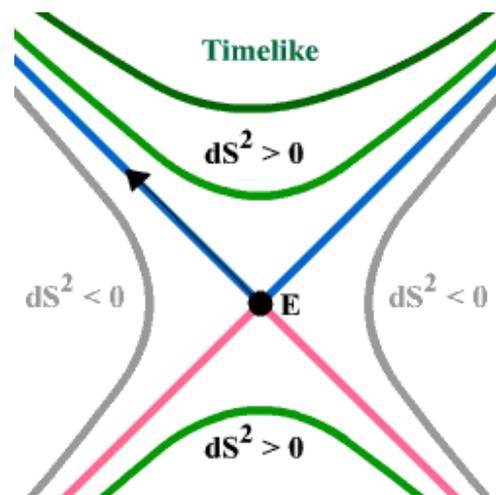
The blue space-time path A represents a flash of light from a laser coming from off of the diagram. The flash of light travels into the future to the space-time event $T=0, X=0$ at which it intersects with the space-time path B. Path B is a vertical line. A vertical line on this diagram means an observer or object at rest in this coordinate system, staying at the same value of X for all time T . In this example, the green space-time path B is the world-line of a mirror standing on a table. The half of the pulse that is not reflected but transmitted is found by continuing path A. The purple space-time path D starts at rest then accelerates and keeps accelerating until it approaches the speed of light.

Our abnormal time traveller is shown on the red space-time path E. Notice this path is a circle, but it isn't like a circle in space - anyone can do that. This path is a circle in space-time. This path keeps going back to the same TIME as well as back to the same SPACE. Notice also that space-time path E is almost always in two places at the same time. What's wrong with this space-time path?

Over 50% of space-time path E is travelling faster than the speed of light!!!

At the top and bottom of the circle, the observer would have to be travelling infinitely fast. We'll explore the difference between normal and abnormal time travellers in the next section.

What is a Light Cone?



Since the observed properties of light were so vastly important in reshaping the mathematical models of space and time in Special Relativity, the propagation of light occupies a very special place in this model. Relativists like to speak of the behaviour of light in terms of light cones. Light cones come in two kinds: past light cones and future light cones. The future light cone of a space-time event E consists of all the paths of light that begin at E and travel into the future. One could imagine a flash of light at event E. The past light cone of a space-time event E consists of all the paths of light that begin at E and travel into the past.

The past light cone of E would be similar to flashes of light all converging at the event E. The past light cone of event E is shown in the figure as the pink diagonal lines to the past of E.

Recall the Minkowski metric: $dS^2 = c^2 dT^2 - dX^2$. The value of dS^2 is important in Special Relativity because it stays the same under a Lorentz transformation. That means all observers moving at constant velocity with respect to each other will agree on the value of dS^2 . If two space-time events are separated by the space-time interval $dS^2 = 0$, then we say

those two points have a light-like separation. Only a light ray, and nothing else, can connect those two space-time events.

The path of an observer travelling less than the speed of light satisfies $dS^2 > 0$. Relativists call that a time-like path. When two space-time events are separated by the interval $dS^2 > 0$, we say those points have a time-like separation. When two space-time events are separated by the interval $dS^2 < 0$, we call that a space-like separation. For events with a space-like separation, there always exists some moving observer who will say those two events happened at the same time. To prove that, look at the Minkowski metric:

Suppose we have a space-like separation with $dS^2 = -1$

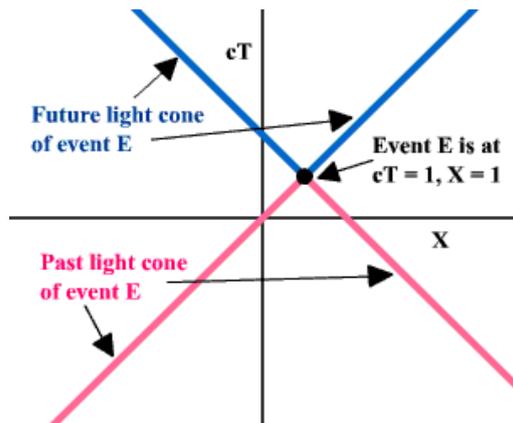
Then we can find a Lorentz transformed coordinate system T', X' so that $dT' = 0, dX' = 1$. This is allowable because it leaves $dS^2 = c^2 dT'^2 - dX'^2 = -1$ unchanged.

The same logic shows that if two space-time events have a time-like separation, then there is no Lorentz transformation to coordinates in which they occur at the same time. This is because the definition of simultaneous in this context is $dT' = 0$.

That would make $dS^2 = -dX^2 < 0$

But if the interval we're starting with has $dS^2 > 0$, any Lorentz transformation will preserve that condition.

The light cone of an event E forms the boundary between all space-time events with a time-like separation from E and all events with a space-like separation from E.



Observe in the figure that the light cone disconnects the past and future time-like areas with areas of space-like separation in a Lorentz-invariant manner, so that the gap between the past and future of an event is absolute and unbridgeable - for all observers. This is how Special Relativity implements causality and makes nontrivial time travel so mentally challenging to cook up! The challenge is to find some way to make the past and future light cones of some event bend around or overlap. But we can't do that in Special Relativity, the light cones in Special Relativity are rigid and unchanging. We need to move up

to General Relativity if we want to try messing with causality.

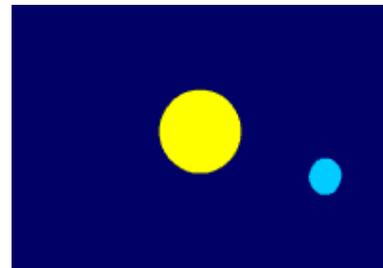
What is Gravity?

Over three centuries ago, Isaac Newton invented a new kind of mathematics called calculus so that he could model motion in the natural world using mathematics. Calculus is about measuring change and so calculus became a vital tool in describing the motions of simple objects.

Newton was able to make a mathematical model that encompassed both objects falling because of gravity on Earth.....



.....and the motion of heavenly bodies in the skies.



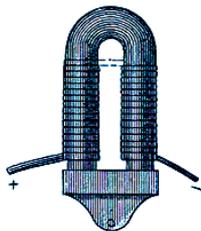
Newton decided that the force of gravity on Earth was the same force that organized the motions of the moon around the Earth and the Earth and all the planets around the sun. He invented a formalism and developed mathematical formulas for calculating the size of the gravitational force both on Earth and in outer space. One of the important formulas in Newton's model is his law for calculating the force of gravity between two objects 1 and 2 with mass m_1 and m_2 , which are separated by a distance R:

$$F_{12} = F_{21} = G m_1 m_2 / R^2$$

The constant G is a number that occurs in Nature, like the speed of light c. The constant G is called Newton's gravitational constant. Newton's law of gravity winds up describing the observed motions of the planets extremely well. Another thing it models quite well is the way the gravitational force felt on the surface of a planet depends on the size and mass of the planet. For example, comparing the gravitational force at the surface of the Earth vs. the moon, we get:

$$F_{\text{moon}}/F_{\text{earth}} = (M_{\text{moon}}/M_{\text{earth}}) (R_{\text{earth}}^2/R_{\text{moon}}^2)$$

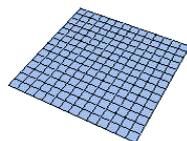
which is about 1/6, and the astronauts who walked on the moon felt it, too. This was an enormous thing Newton did - to invent a new kind of mathematics to build a model that described in the same formula the observed motion of both falling objects on Earth and the planets in the heavens. BUT unfortunately, Newtonian gravity falls apart when we try to combine it with what we've just learned about Special Relativity. Newton's model for gravity looked pretty good until scientists started learning more about the force of electromagnetism. They learned that light was made of electromagnetic waves, and that they could model the observed behaviour of light very well by looking at solutions of the wave equation for the electromagnetic field. When they looked at those wave equations, they could see that causality and Special Relativity were both already there.



The mathematical equations that modelled electromagnetism were consistent with causality and Special Relativity. But Newton's law of gravitation depends only on the distance between two massive objects at a given moment in time. Newton's law doesn't model what happens when the gravitational field changes in time. There was no wave equation to be had from Newton's model of gravity and there wasn't a way to make it consistent with causality and Special Relativity. (Plus, Newton had spent a lot of time convincing himself that light was not wavelike in nature, so his theories really needed updating by the time electromagnetism came around.)

This was where Einstein came in. Not only did Einstein give us the Special Theory of Relativity, but in his quest to make gravity consistent with Special Relativity, he invented the General Theory of Relativity. And what a can of worms that opened up, as we shall see later.

What is General Relativity?



We've described the Euclidean (or Euclidean-Mesopotamian) metric in two space dimensions:

$$dL^2 = dX^2 + dY^2.$$

We've discussed the complications that arise with the addition of time to space to give the Minkowski metric:

$$dS^2 = c^2 dT^2 - dX^2$$

shown here 1 dimensional.

What else can we do to our space-time distance function to make life more interesting (and hopefully solve the problem with Newtonian gravity discussed in the last section)? What if we play around with the form of the Minkowski metric? It turns out that if the space-time metric is arranged in the right manner, we can get something called space-time curvature. And that is what the General Theory of Relativity is all about.

For example, suppose we add some extra space and time dependence to the Minkowski metric to make a new space-time distance function

$$dS^2 = g_{TT}(T,X) c^2 dT^2 - g_{XX}(T,X) dX^2$$

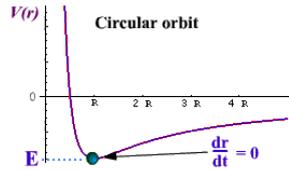
Using differential geometry, taking the right combination of first and second derivatives of $g_{TT}(T,X)$ and $g_{XX}(T,X)$, we could calculate the what is called the curvature tensor R_{uv} for this choice of space-time distance function. The subscripts on R_{uv} are called tensor indices and refer back to the coordinates used in the metric. The Minkowski metric corresponds to the choice $g_{TT} = g_{XX} = 1$ and it has $R_{uv} = 0$ for all values of the tensor indices. This is why the Minkowski metric is known also as flat space-time - because the space-time curvature calculated from this distance function is zero. In Einstein's time they were already learning about differential geometry, but Einstein motivated this field of mathematics even more when he came up with an equation relating the curvature tensor of the spacetime distance function to the distribution of matter and energy in spacetime, encoded in a tensor T_{uv} called the stress-energy tensor. This equation is now called the Einstein equation:

$$R_{uv} - (1/2) g_{uv} R = (8 \text{ Pi } G/c^4) T_{uv}$$

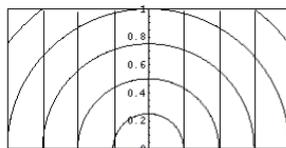
This equation (or actually, set of equations, for there is an equation for every combination of tensor indices u and v) models a lot of phenomena in the Universe that was impossible to describe with mathematics just using Newton's law of gravity. For example, observations of the bending of light by gravity, gravitational radiation emitted by pulsars, new observations of black holes and the observed expansion of the visible Universe can all be modelled rather successfully using this elegant formalism uncovered by Einstein.

Most people have heard the phrase: A straight line is the shortest distance between two points. But in differential geometry, they say this same thing in a different language. They

say instead: Geodesics for the Euclidean metric are straight lines.



A geodesic is a curve that represents the extreme value of a distance function in some space or space-time. Geodesics are important in the relativistic description of gravity. Einstein's Principle of Equivalence, part of the G. T. of R., tells us that geodesics represent the paths of freely-falling particles in a given space-time. (Freely-falling in this context means moving only under the influence of gravity, with no other forces involved.)



When our distance function is the Pythagorean Rule

$$dL^2 = dX^2 + dY^2,$$

also known as the Euclidean metric, straight lines are the curves that give the minimum Euclidean distance between two points. In two space dimensions there are many metrics one can dream up in addition to the Euclidean metric.

For example, take a class of metrics of the form:

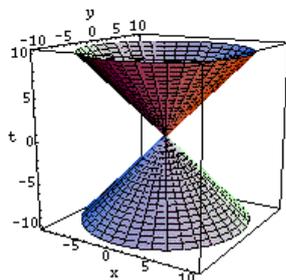
$$dL^2 = (k^2/Y^2) (dX^2 + dY^2)$$

For $Y > 0$, this distance function or metric is called the *Poincare upper half plane*. The geodesics for this metric are described by the formula:

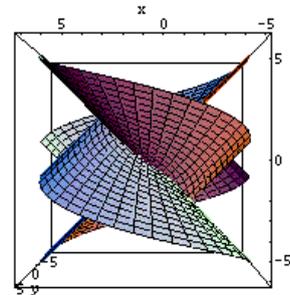
$$(X - X_0)^2 + Y^2 = k^2/h^2$$

The geodesics consist of two types of curves: a) semicircles of radius k/h centred at $X = X_0$ and in the limit $h = 0$, vertical lines with $X = X_0$

Things get more complicated when we graduate from space to space-time.



Remember that the Minkowski metric has a space-time distance function dS^2 that can be negative, positive or zero; whereas the distance functions in space dL^2 can only be positive. This means we have to separate our geodesics on the basis of whether the distance function dS^2 is positive, negative or zero. Geodesics with $dS^2 < 0$ are called space-like geodesics. Geodesics with $dS^2 = 0$ are called null geodesics. Geodesics with $dS^2 > 0$ are called time-like geodesics. The behaviour of time-like and null geodesics is the most important for understanding time travel. Time-like geodesics behave the opposite from geodesics in space.



They actually represent the longest space-time distance between two space-time events. In Minkowski space-time, all of the geodesics are straight lines, whether time-like, space-like or null. The light cones are made of the null geodesics, and they rigidly separate the past from the future. In flat space-time in two space and one time dimensions, the light cones really do look like cones, as shown in the figure to the right.

But in a generic curved space-time, the null geodesics won't as a rule be straight lines, sometimes they can be more interesting.

The light cones made from null geodesics from a space-time metric in a curved space-time can even be made to have the past and future light cones overlap. An example of a spacetime satisfying the Einstein equations in three spacetime dimensions (two space and one time) where the past and future light cones overlap is shown in the figure above right. We'll see more of this spacetime later. See how it's twisted? Angular momentum can twist light cones and even make time travel possible in theory if not in practice. General Relativity didn't make Newtonian gravity false. Newton's model is still a good model for most measurements and calculations of the motion of planets and rockets and so forth, and General Relativity must agree with Newton's model in that limit. Here is proof that these two very different models agree on the motion of the Earth around the Sun but disagree in the region where a new relativistic phenomenon - the black hole - is present in Einstein's model but not in Newton's.

In Newton's model of nature based on the math he invented, the differential calculus, the primary equation by which motion of objects is calculated is Force = mass x acceleration. This gives a set of second-order differential

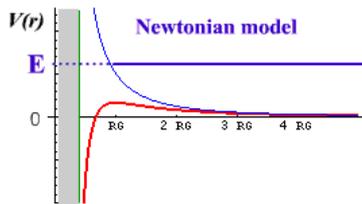
equations and when we solve that system, we get the motion of the object in question when subjected to the force in question. If the object in question is the Earth and the force in question is the gravitational force of the Sun on the Earth, then after writing the equation in spherical coordinates, we get the following equation for the change in time of the radial coordinate r for the position of the Earth.

$$m \left(\frac{dr}{dt} \right)^2 = 2 (E - V_N(r))$$

$$V_N(r) = - M m G/r + m (L/m)^2 / (2 r^2)$$

G is Newton's gravitational constant, M stands for the mass of the Sun and m is (approx.) the mass of the Earth. Because the Newtonian force law for gravity depends only on radial distance, not on time or angle, there are two constants of motion called angular momentum L and energy E . The function $V(r)$ is plotted for the Earth/Sun system. Notice that whenever $V(r) = E$, the radial coordinate stops changing because $dr/dt = 0$

These are called turning points. The turning points classify the type of orbit, as shown in the figure. Notice that it is the L^2/r^2 term in the potential that causes the turning points for smaller r . Angular momentum acts almost like a force of repulsion to counter gravitational attraction. That will be important later as an agent of causality violation in the relativistic model.



In General Relativity, the first ingredient in model-making is the space-time metric. This metric must solve the Einstein equation that relate the spacetime curvature to the matter and energy present.

If the matter and energy present is idealized by a point-like object of mass M , then the spacetime metric that solves the Einstein equation is called the Schwarzschild metric. We won't display that metric here for the sake of brevity. The time-like geodesics are easy to calculate for the Schwarzschild metric. We wind up with an equation that looks a lot like the Newtonian formula above:

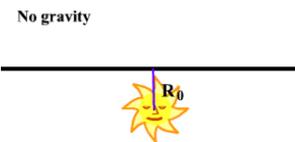
$$m \left(\frac{dr}{dt} \right)^2 = 2 (E - V_R(r))$$

$$V_R(r) = - M m G/r + m (L/m)^2 / (2 c^2 r^2) - M G m / (L/m)^2 / (2 c^2 r^3)$$

At large distances from the Sun, the last term in the potential $V_R(r)$ can be neglected, and the classification of orbits is the same as for the Newtonian case. But if the Sun really were a pointlike mass, the last term in the potential $V_R(r)$ would give us trouble. Notice in the figure

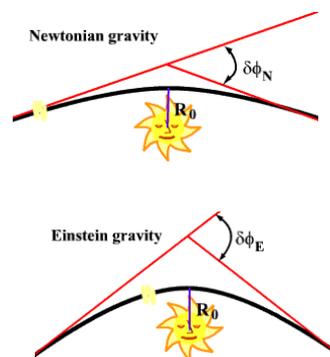
the red line, which represents the relativistic potential, veers down to become infinitely negative, instead of infinitely positive as with the Newtonian potential. This behaviour is the signal of a black hole. We can't go into that in depth right here, but you can read about it in books specializing in black holes. The Sun is not pointlike, the mass of the sun is spread within a radius of about 700,000 kilometres. The black hole behaviour would not set in unless the mass of the Sun were confined to a within radius of about three kilometres.

Einstein was very lucky because data that fit predictions of his new mathematical model was observed in light from stars during a solar eclipse in 1919, very soon after his model became public.



The deflection of light around the Sun was one such predictive success of General Relativity. The deflection angle $\delta\phi$ tells us how far away from a straight line the path of the light pulse in question was deflected by the Sun. The deflection angle is by definition zero when there is no gravity. We need to compare the deflection angles calculated using the Newtonian and relativistic models for gravity and spacetime. The turning point R_0 is the closest distance that the light pulse gets to the Sun.

We'll standardize our coordinate system so that $f=0$ corresponds to $R = R_0$, and calculate $\delta\phi$ that way. Without gravity, both Newtonian and relativistic models say the path is a straight line.



The path of a straight line in polar coordinates centred at the centre of the Sun would be: $1/r = (1/R_0) \cos(f)$ where R_0 is the turning point mentioned above. First we want to find Df which is the total angle swept out by the light pulse from the start to the end of its journey across space-time. Imagine the straight line path extending infinitely far to the right and left. When $r = \text{infinity}$, by symmetry of our coordinate system we have:

$$0 = (1/R_0) \cos(Df/2)$$

Therefore $Df = p$ is the total difference in angle swept out by the light pulse as it comes in from infinitely far away and travels back out infinitely far away. The deflection angle here is $df = Df - p = 0$, as it should be for a straight line. Newtonian gravity doesn't work well for describing the properties of light, which can be modelled like the propagation of a massless particle. But it is possible to fake it by using the equation for a Newtonian hyperbolic orbit:

$$\frac{1}{r} = \frac{GM(m/L)^2}{L^2} (1 + e \cos(f))$$

$$e = \left(1 + \frac{2E/m}{L/GMm^2}\right)^{1/2}$$

where the eccentricity e is a function of the incoming particle's energy E , mass m and angular momentum L .

The turning point

$$R_0 = (L/m)^2 / (GM(1+e))$$

In General Relativity, the path of a light pulse is described as a null geodesic satisfying the geodesic equation for the Schwarzschild metric, the distance function that solves the Einstein equations around a massive object in outer space such as the Sun. An approximate equation for the trajectory is:

$$1/r = (1/R_0) \cos(f) + ((GM/c^2)/R_0^2) (2 - \cos^2(f))$$

The term $\cos^2(f)$ can be neglected if the deflection angle df is very small and $Df/2$ is close to $p/2$. Therefore, to lowest order in df we get:

$$0 = (1/R_0) \cos(Df/2) + 2 (GM/c^2)/R_0^2 - \cos(p/2 + df/2)$$

$$= \sin(df/2) \sim df/2$$

$$= 2 (GM/c^2)/R_0$$

Therefore $df_E = 4 (GM/c^2)/R_0 = 2 df_N$ is the deflection angle for light found by using null geodesics in the Schwarzschild metric according to General Relativity.

Observations of starlight deflected around the Sun were made during solar eclipses beginning in 1919, and the measurements supported Einstein's model, not Newton's which predicts an angular deflection of half the size that was observed.

We've already shown that paths of light are bent by gravity. Another way of stating this is spacetime curvature acts like a lens, hence the term gravitational lensing.

Under certain circumstances, gravitational lensing can fool us into thinking we are seeing several space-time events, when in fact we're seeing several images of a single space-time event. The figure shows how a single flash of light behind a very massive object M in two space dimensions can be perceived as two simultaneous flashes of light coming from opposite directions by a viewer in front of M .

Gravitational lensing means that the light cone of an event can be distorted by matter and energy. The possibility of distorting light cones is crucial to the possibility for nontrivial time travel. In the case of multiple images, the light cone of the event in question has developed a crease in it, it has overlapped with itself.

Multiple images are observed in our Universe today. The following image has a picture of a very complex multiple image system photographed by the Hubble Space Telescope in 1995 and shows multiple images of a distant galaxy where the light has been bent round some massive object, possibly a black hole.



The image was taken with the Wide Field Planetary Camera 2. Credits: W.Couch (University of New South Wales), R. Ellis (Cambridge University), and NASA

- We will see more of this later, in Warp Factor 3

Graham Hodson

(Adapted from a PowerPoint presentation delivered at the Godlee Observatory)

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