Cosmology for the Cosmic Engine

Background Theory and Simple Ideas to Enhance Teaching in Stage 6 Physics

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Cosmology is the scientific study of the origin and evolution of the Universe. As such it obviously seeks to address some of the most profound questions in science. It is a lively and rapidly evolving field of inquiry. Technological improvements within the last decade have led to discoveries that have radically altered our understanding of the Universe.

Module 8.5 *The Cosmic Engine* (NSW Stage 6 Physics Syllabus) specifically requires:

	Students learn to:	*Students:*
1. Our Sun is just one star in the galaxy and ours is just one galaxy in the universe	▪ outline the historical development of models of the Universe from the time of Aristotle to the time of Newton	▪ identify data sources, and gather, process and analyse information to assess one of the models of the Universe developed from the time of Aristotle to the time of Newton to identify limitations placed on the development of the model by the technology available at the time
2. The first minutes of the Universe released energy which changed to matter, forming stars and galaxies	▪ outline the discovery of the expansion of the Universe by Hubble, following its earlier prediction by Friedmann ▪ describe the transformation of radiation into matter which followed the 'Big Bang' ▪ identify that Einstein described the equivalence of energy and mass ▪ outline how the accretion of galaxies and stars occurred through: – expansion and cooling of the Universe – subsequent loss of particle kinetic energy – gravitational attraction between particles – lumpiness of the gas cloud that then allows gravitational collapse	▪ identify data sources and gather secondary information to describe the probable origins of the Universe

Background Science

In this section we will discuss some of the observational and theoretical evidence that must be taken into account in constructing a cosmological model. Although competing models do exist and are vigorously argued by some in the scientific literature, the vast majority of practising cosmologists/astrophysicists would use a big bang model in one or more of its variations to account for the universe.

Cosmology has rapidly evolved from being a branch of science renowned for low precision and lack of data to being a very high precision field. Any modern model or theory of the Universe must account for observations. Most current models adopt the cosmological principle.

The Cosmological Principle

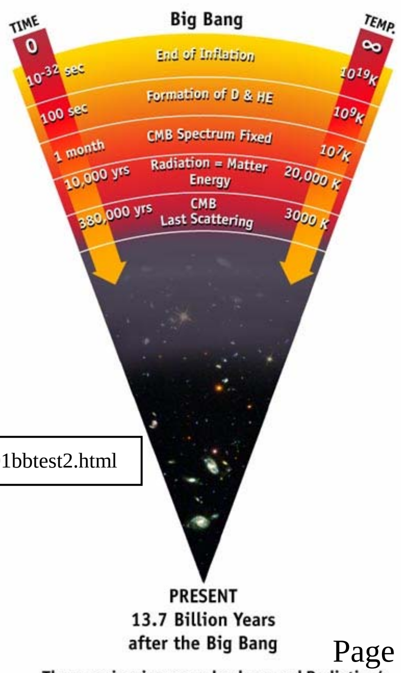
This asserts that on a sufficiently larger scale the Universe is the same in every place and appears the same no matter what direction you look. More formally such a universe is said to be *homogeneous* (identical everywhere in space) and *isotropic* (appears same in every direction).

The Big Bang Theory

As the syllabus uses the above term it may be worth spending time discussing with students what is meant by the term theory in a scientific context. Whilst many practising cosmologists and astronomers may prefer to use the term model a scientific theory is one supported by significant observational or experimental evidence. As a model, the Big Bang has several free parameters, some of which are now fairly well constrained. Whilst the Big Bang model is currently the most widely accepted and successful model it has limitations and some problems yet to be resolved.

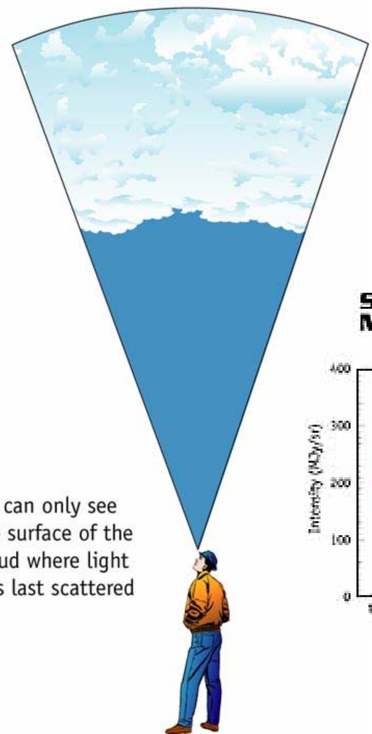
The Big Bang model rests on several key pieces of evidence:

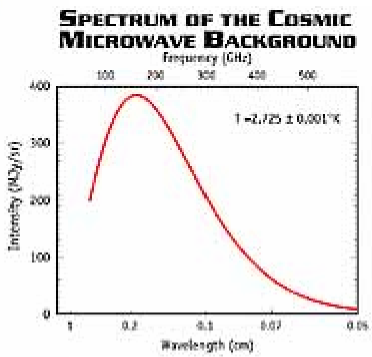
- **The Universe is expanding**. This expansion was first detected by Edwin Hubble in the 1920s by measuring the redshift of galaxies. His results showed that the further a galaxy is from us, the faster it is receding from us. This is not due to the motion of the galaxy itself which may be in any direction relative to us. Instead it is due to the expansion of space itself. The relationship between recession velocity and distance is a linear one and is now known as Hubble's Law. A major goal of astronomers since its discovery has been to accurately measure Hubble's Constant, H_0, the current expansion rate of the Universe. The two best current value for Hubble's Constant, are:
  WMAP: $H_0 = 71 \pm 4$ km s^{-1} (5% margin)
  HST Key Project: $H_0 = 71 \pm 6$ km s^{-1}
  which in turn suggest that the Universe is 13.7 billion years old.
- **Cosmic Microwave Background Radiation (CMBR)**. This is the remnant radiation from the Big Bang. As the Universe has expanded the energy density has dropped so the initial



The cosmic microwave background Radiation's "surface of last scatter" is analogous to the light coming through the clouds to our eye on a cloudy day.

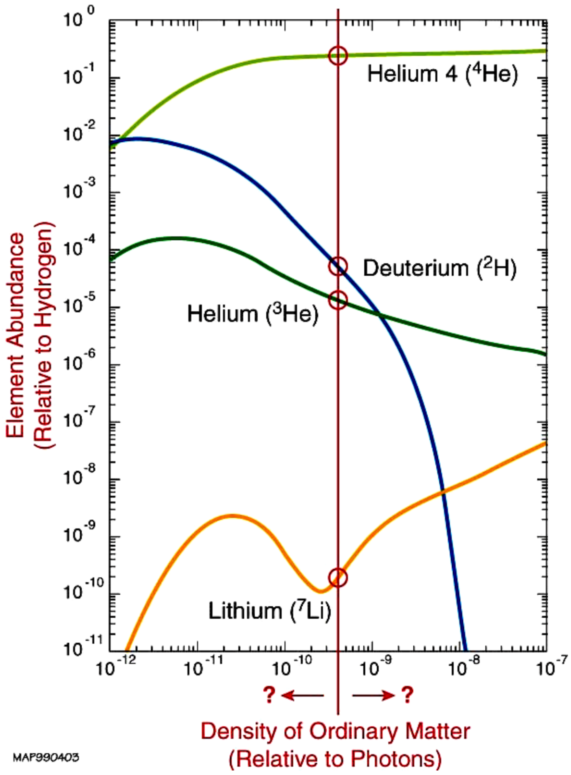
http://map.gsfc.nasa.gov/m_uni/uni_101bbtest2.html





temperature of 10^{19} K at the end of the Inflationary era has cooled to an average background temperature of 2.72 K. This corresponds to a peak wavelength that corresponds to microwave frequencies. The CMBR was first detected in 1963 by Penzias and Wilson for which they were awarded the 1978 Nobel Prize for Physics.

- **The ratio of primordial elements**. The Big Bang model makes predictions about the relative primordial ratios of the light nuclei; hydrogen, deuterium, helium-3, helium-4 and lithium. Observational results fit the model. (see at right) This baryonic matter is ~75% H and ~25% He by mass.



- **The formation and distribution of large-scale structure in the Universe.** The minute irregularities present in the early Universe have grown due to a slight increase in gravitational attraction over surrounding material. Eventually matter would clump together and continue to grow, forming large gravitationally bound clusters of galaxies. This large-scale structure has been a particularly active field of research over the last decade. Large scale surveys such as the Australian 2dF Galaxy Redshift Survey on the Anglo-Australian Telescope have proved invaluable in helping test and extend our understanding of this field.
- **Observed evolution.** Recent improvements in telescopes and instrumentation now allow us to observe distant (hence normally interpreted as old ∴young) galaxies. They do not look the same as nearby galaxies thus suggesting that they have changed over time. The fact that the Universe has changed over time became evident in the late 1950s and early 1960s via radio surveys of the sky. Bright, extragalactic sources are not randomly distributed
- **Quasars.** These extremely luminous, high-redshift objects are thought to be supermassive black holes in the centre of early galaxies. The absence of any nearby quasars again supports the idea that the Universe has evolved. Recent observations show that quasars with supermassive black holes with a mass of 10^9 solar masses in their cores had formed within a billion years of the Big Bang.

Problems with Big Bang Model

(summarised from *An Introduction to Galaxies and Cosmology*, Ed Mark H. Jones and Robert J. A. Lambourne, The Open University, Cambridge University Press, 2004.)

1. What is dark matter? (CDM – neutralino best current candidate)
2. What is dark energy? (Candidates include Einstein’s cosmological constant, quantum vacuum energy and quintessence).
3. Why is the Universe so uniform? (The horizon problem – why are widely separated parts of the Universe at same temperature and density? Inflation may provide an answer)
4. Why does it have a flat geometry (k = 0)? (Inflation may have smoothed the Universe out)
5. Where did the structure come from?
6. Why is there more matter than antimatter? (Grand unified theories allow for 1 in 10^9 parts of matter in excess to antimatter.)
7. What happened at t = 0? (This awaits unifying General Relativity with quantum gravity. M-theory may provide clues).
8. Why is the Universe the way it is? (Anthropic principle?)

Inflation
The Inflationary theory was proposed in the early 1980s to address the horizon problem and the flatness of the Universe. It suggests that from 10^{-35} to about 10^{-30} seconds after the big bang the Universe increased enormously in size by a factor of up to 10^{50}. This phase transition was triggered by the breaking of symmetry when the electromagnetic and strong forces separated. Smoothing resulting from this rapid expansion erased primordial irregularities such as magnetic monopoles and domain walls. Quantum fluctuations, however, were boosted in size to become the basis for later structure such as galaxies.

Concepts to Emphasise

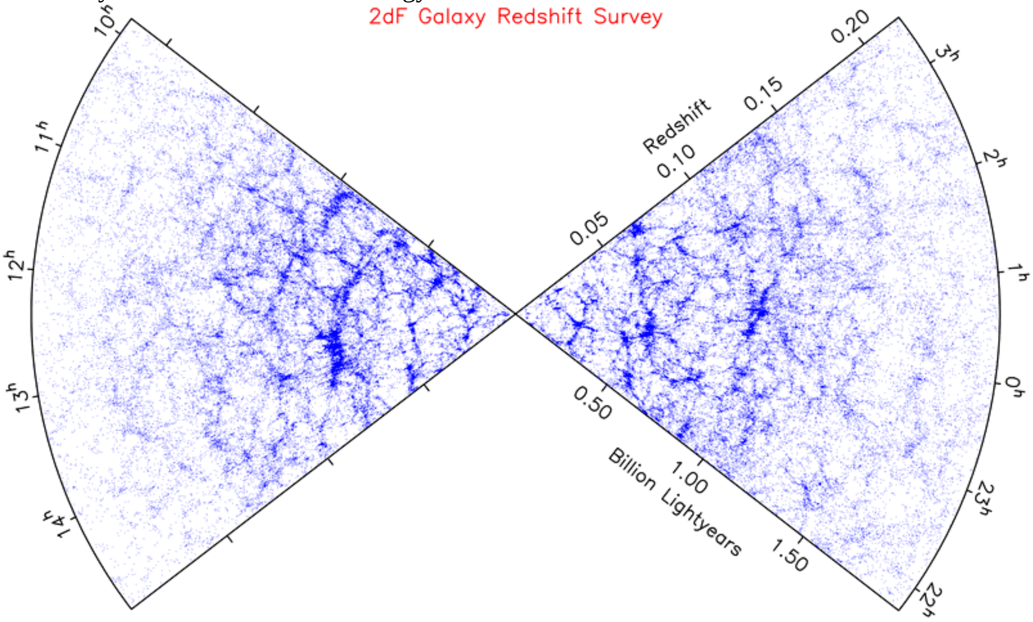
1. **The Big Bang** was not an explosion. Most books and portrayals of the big bang incorrectly depict it as some form of explosion. This is a mistake. If it was an explosion it must explode from somewhere to somewhere else. This leads to point 2.
2. **The centre of the Universe**. This is always a conceptually challenging idea for students. It is natural to think that the Universe must have a centre. In fact, going back to point 1 above, the centre of the Universe is all around us. Actually the big bang occurred all around us. The Universe does not have a centre in much the same way as the surface of a sphere has no centre. By creating space itself
3. **Galaxies are not moving through space**. To clarify this, what we are really talking about are galaxies moving through space on a cosmological scale. In fact all galaxies show relative motion through space, typically 300 km s^{-1}. Some nearby galaxies are actually moving towards us. Once this is accounted for, the so-called Hubble expansion is due to the fact that space between galaxies is expanding rather than galaxies all moving through space away from us.
4. The issue of **formation of structure** of galaxies, clusters of galaxies and large-scale structure is one still being resolved. In general "top-down" scenarios have fallen out of favour compared with bottom-up or hierarchical scenarios with cold dark matter (CDM). In these, very high-mass stars form first then form structures equal in mass to globular clusters that then form the protogalaxies. These smaller galaxies, typically of 10^6 $M_{\odot}$ then produce the larger 10^{11} $M_{\odot}$ galaxies seen today through collapse and mergers.
   The initial process leading to structure formation comes from gravitational instabilities in the distribution of matter produced in the big bang. By matter we include the baryonic matter such as protons and neutrons and non-baryonic matter that comprises sold dark matter. As yet we still do not know what this CDM is comprised of but currently the *neutralino*, a supersymmetric particle, is the best candidate. *Cold* means that it is slow moving or has non-thermal energies; *dark* means it does not emit or radiate light and *matter* because it interacts gravitationally.
5. **The Big Bang model is currently the most widely accepted and successful model.** There are still several key questions that remain unanswered but work continues on them. It serves as a useful example of science in action. The big bang paradigm has replaced steady state alternatives. There are other models that some researchers discuss (plus a wealth of fringe or crackpot theories, most of which set out to prove Einstein wrong) but they are not widely accepted.

Australian Contributions

Australian scientists have played an active role in recent developments in cosmology. A few of these are outlined below.

1. The **2dF Galaxy Redshift Survey** (http://www.mso.anu.edu.au/2dFGRS/) and **2dF Quasar Redshift Survey** (http://www.2dfquasar.org/) were complementary projects using the **2dF instrument** (http://www.aao.gov.au/2df/)on the 3.9 m Anglo-Australian telescope at Siding Spring. This amazing instrument was designed and built by AAO scientists and engineers and is able to take 400 separate spectra simultaneously whilst a robotic arm places small prisms on another plate so that another 400 can be obtained for a different field with minimal lose of observing time. The 2dF GRS obtained spectra of almost 250,000 galaxies in two wedges in the sky. Analysis of the data has provided a wealth of information to astronomers including a limit on the total neutrino mass, the mass limit and spatial distribution of dark matter and, in

combination with CMBR data, precise measurements for the Hubble Constant, and baryon density and evidence for dark energy.



2. The leader of one of the two teams that observed distant Type Ia supernovae to determine the geometry of the Universe was Professor Brian Schmidt from ANU. His **High-Z SN Search** team (http://cfa-www.harvard.edu/cfa/oir/Research/supernova/HighZ.html) found evidence that the Universe is actually accelerating, a result dubbed by the prestigious journal Science the top research advance of 1998.
3. Australia is at the forefront is planning the next generation radio telescope, the **SKA or Square Kilometre Array** (http://www.askac.org/) that will play a key role in observing the early universe and improve our knowledge about the era of reionisation.

Classroom Activities & Ideas

There are many simple activities, analogies and ideas to help convey cosmological concepts in the classroom.

The expanding universe. How best to model or convey the idea that a universe can expand yet not have a centre? Several methods can be employed.

1. **Balloons**. Students can mark a balloon with several dots, each with a number or letter. Blow the balloon up slightly then using string, measure the distance from, eg A to B, A to C and so on and record. Blow the balloon up a bit more and repeat measurements. Do this a third time then study the data. Students should see that the greater the distance initially between two dots, the greater they move apart over time relative to nearby dots. If you use the simple relationship that velocity (speed) = distance/time and take each additional inflation as one time unit they can calculate that more distant dots actually move apart faster than nearby dots. This is the essence of Hubble's Law.
   One problem with the balloon analogy is that the dots students draw (which are supposed to represent clusters of galaxies) actually expand when they blow up the balloon. In reality galaxies themselves do not expand as the Universe ages. It is not the galaxies that are even moving at all, rather it is the space between them that is expanding. Balloons can also be used to try and convince students that the concept of the centre of the universe is meaningless. Ask them where is the centre of the surface of the balloon (or of the Earth)? Obviously the balloon's surface is only two-dimensional whereas the universe has extra dimensions but the analogy is sound. To show there are no preferential locations ask them to repeat the initial activity measuring all distances from point B or C. Again, they should see that from B's perspective, all the points move away over time.
   Of course, having balloons in the classroom may also lead to real "big bangs" in cases of over-inflation. Students may also experience deflationary universes! ☺

2. **Balloons 2 – the CMBR**. Draw a transverse wave on a balloon. As you blow the balloon up the wave stretches out to longer wavelengths just as radiation is redshifted in an expanding universe.

3. **Dough & sultana models.** Dough mixed with sultanas and yeast prepared before a class can be left to naturally expand. An advantage of this approach is that the sultanas do not expand though it is harder to perform quantitative measurements.

4. **Overlays of expanding space**. The Astronomical Society of the Pacific's (http://www.astrosociety.org/index.html) *Universe at Your Fingertips* resource manual contains an excellent activity by David Chandler *Visualizing the Expansion of Space*. It uses two seemingly identical images of the Universe where one is photocopied onto a transparency and overlaid on the other. Using both images as transparencies allows you to show it on an OHGP for quite dramatic effect. (Copies of this handed out during the workshop). The manual also contains other relevant activities for classroom use.

5. **Physiotherapy in Space.** Many ageing educators (including me) have a *Theraband* for physiotherapy. These are really useful for demonstrating the expansion of space. Get two students, each holding one end to stand at the front of the room. Other students stand behind the band and each put a large, different coloured peg onto it. The pegs represent galaxy clusters. As the band is stretched, each student can see the distance to the other pegs or students increase but the ones further away move even more than the nearby ones. Another option with a theraband is to lay it flat and draw a transverse wave on it. This represents the background radiation or indeed radiation emitted from a source. As you stretch the band, the wave is also stretched out to a longer wavelength or lower frequency.

6. **Computer simulation of formation of large-scale structure.** There are several sites that allow you to view supercomputer simulations of the formation of galaxies, star clusters and large-scale structure. These are useful in conveying the role of simulation and mathematical modelling in modern cosmology and astrophysics.

7. **Computer-based activities.** Software-based activities such as those provided by *Project CLEA* (see resources at end) provide an interesting and effective way of engaging students and demonstrating some of the principles and technologies involved. The CLEA activities are free and come with detailed manuals as well as pre and post-tests.

8. **The CMBR on TV.** About 1% of the noise or "snow" seen on a TV screen is actually due to the CMBR. Turn on a TV and turn to a channel between normal stations. Part of the noise truly comes from the Big Bang. This is a handy introduction to a lesson.

Online Resources

- *2dF Galaxy Redshift Survey* (http://www.mso.anu.edu.au/2dFGRS/)
- *2dF Quasar Redshift Survey* (http://www.2dfquasar.org/)
- *An Atlas of the Universe* (http://www.anzwers.org/free/universe/index.html) is an excellent site that provides a large set of graphics showing the scale of the Universe zooming out from the Sun.
- *An Introduction to the Cosmic Microwave Background Radiation* (http://background.uchicago.edu/~whu/beginners/introduction.html) is an excellent guide written by Wayne Hu, a cosmologist from University of Chicago. It provides effective graphics, useful analogies and concise, clear summaries.
- *Bad Cosmology* (http://www.jb.man.ac.uk/~jpl/cosmo/bad.html) has a set of concise answers to key misconceptions. Reasonably technical but worth checking.
- *BBCi - Space -Cosmology Animation* (http://www.bbc.co.uk/science/space/playspace/cosmology/)is an effective Flash movie outlining the history of cosmology up to Galileo.
- *BBCi - Space - Origins* (http://www.bbc.co.uk/science/space/origins/index.shtml) from the BBC provides a concise and clear set of pages on the origin and fate of the Universe

- *The Big Bang Theory - An AskERIC Lesson Plan* (http://www.geminfo.org/Workbench/training/SPA0010.htm) is a class activity that simulates how we investigate the Big Bang, Suitable for grade8-9.
- *Celestia: A 3D Space Simulator* (http://www.shatters.net/celestia/) is an outstanding free software package with a wealth of add-ons. It is a multi-platform package (Windows, Mac OS, Linux, Unix) that allows you to visualise our Solar System and galaxy using real astronomical data. You can "fly" to other stars, visit the planets and even piggybank on any of the current or planned spaceprobes. Excellent educational add-ons and interactive learning documents including one on stellar evolution are available from another site (http://www.fsgregs.org/celestia/).
- *CERES: The Expanding Universe* (http://btc.montana.edu/ceres/html/Universe/uni1.html) is an excellent, detailed set of six classroom activities dealing with the Hubble Law and expansion. Comes complete with Teacher Lesson Plans, student worksheets, evaluation, mapping to US education standards and background science.
- *Computer Simulations of Cosmic Evolution* (http://www.astro.washington.edu/weblinks/Universe/Simulations.html) provides over a dozen animations on galaxies and formation of large-scale structure.
- *Cosmic Mystery Tour* (http://archive.ncsa.uiuc.edu/Cyberia/Cosmos/CosmicMysteryTour.html) is a set of pages that take you through the formation and evolution of the Universe and the formation of galaxies. Its focus is on using animations, images and short video explanations by astronomers to convey concepts. Well worth visiting.
- *Cosmic Survey - What are your ideas about the Universe?* (http://cfa-www.harvard.edu/seuforum/teachers/L3/survey/survey.htm) is an effective set of exercises on scale; size, distance and age of objects in the Universe. Need to convert to SI units.
- *ESA - Education - High School - Big Bang* (http://www.esa.int/export/esaED/SEMTB99YFDD_highschool_0.html) is a brief description of the standard big bang model at an appropriate depth for high school students by the European Space Agency. Has links to related articles.
- *Friedmann* (http://www-gap.dcs.st-and.ac.uk/~history/Mathematicians/Friedmann.html) is a useful, detailed page on Alexander Friedmann.
- *The Hidden Lives of Galaxies,* (http://imagine.gsfc.nasa.gov/docs/teachers/galaxies/imagine/titlepage.html) a 2.2 MB NASA PowerPoint presentation, lesson plans and teaching guide.
- *High-Z SN Search* (http://cfa-www.harvard.edu/cfa/oir/Research/supernova/HighZ.html)
- *Hot Big Bang* (http://www.damtp.cam.ac.uk/user/gr/public/bb_home.html) is a cosmology site from Cambridge University that has effective summaries. It discusses the key evidence and some problems with the standard model.
- *HSC The Cosmic Engine* (http://www.phys.unsw.edu.au/hsc/cosmic.html) is a useful set of notes with links and activities by Associate Professor Michael Burton, an astrophysicist at UNSW.
- *LIFE'S BIG QUESTIONS: How did the Universe Begin?* (http://www.pbs.org/safarchive/4_class/45_pguides/pguide_501/4551_universe.html) is a set of activities and a lesson plan for exploring the Big Bang. From PBS in America.
- *Listening to the Big Bang* (http://www.abc.net.au/science/slab/watson/story.ht) is an ABC online article by Dr Fred Watson, Officer in Charge of the Anglo-Australian Telescope at Coonabarabran and well known populariser of astronomy on the radio. This is a short article that clearly describes the Big Bang and addresses several common misconceptions. Useful as an article for in-class reading and comprehension at Stage 5.
- *Ned Wright's Cosmology Tutorial* (http://www.astro.ucla.edu/%7Ewright/cosmolog.htm) has a wealth of information including an excellent set of answers to FAQs in cosmology. The site uses high school mathematics. His site also has a useful discussion of cosmology and religion.

- *Physics: The Cosmic Engine* (http://science.uniserve.edu.au/school/curric/stage6/phys/cosmeng.html) is an excellent set of annotated links by the UniServe Science team at University of Sydney.

- *Powers of 10* is a famous film showing the scale of the Universe by changing the view by a factor of ten every ten seconds. An online zoomable version (http://micro.magnet.fsu.edu/primer/java/scienceopticsu/powersof10/) is useful whilst the commercial site with more details and material for purchase is also available (http://www.powersof10.com/#).

- *Project CLEA* (http://www.gettysburg.edu/academics/physics/clea/CLEAhome.html) allows you to download free programs and manuals that allow you to simulate observing, obtaining and analysing data. *The Hubble Redshift-Distance Relation* and *Large-Scale Structure of the Universe* are particularly relevant for this module whilst others are excellent for 9.7 Astrophysics. These are excellent simulations that utilise real data.

- *Recovering Hubble's Original Data* (http://jersey.uoregon.edu/vlab/hubble/Hubble_plugin.html) is a Java applet that simulates Hubble's observations.

- *Science Cartoons Plus – The Cartoons of S. Harris* (http://www.sciencecartoonsplus.com/gallery.htm) has dozens of cartoons by Sidney Harris related to astronomy and physics. They can provide an amusing way to provoke questions and discussion among students.

- *Science, Intelligence and Creativity: Introduction to Cosmology* (http://www.star.qmul.ac.uk/~rmh/cosmology.html) is a concise set of pages that clearly outline the key points in the hot big bang cosmological model. It discusses Inflation as well as current problems with the standard model. Written by a theoretical cosmologist from Queen Mary, University of London.

- *SkyServer* (http://skyserver.sdss.org/) is the educational home page for the massive Sloan Digital Sky Survey. It has a wealth of material for teachers and students at a variety of levels. There are some excellent tutorials and many projects offered, some of which are open-ended.

- *Universe! - EXPLORE: Beyond the Big Bang* (http://cfa-www.harvard.edu/seuforum/explore/bigbang/bigbang.htm) is an excellent site with questions and answers plus sections on current research.

- *Universe in a box: formation of large-scale structure* (http://cosmicweb.uchicago.edu/sims.html) from the Center for Cosmological Physics at the University of Chicago has a set of pages and animations of supercomputer simulations on how large-scale structure forms. It discusses cold dark matter models.

- *WMAP Cosmology 101: Our Universe* (http://map.gsfc.nasa.gov/m_uni/uni_101ouruni.html) provides a clear introduction into modern cosmology. Perhaps too detailed for most students it is however useful for teachers and students who want more detail.

Contact Details

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