Ex-nihilo II: examination syllabi and the sequencing of cosmology education

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Abstract
Cosmology education has become an integral part of modern physics courses. Directed by National Curricula, major UK examination boards have developed syllabi that contain explicit statements about the model of the Big Bang and the strong observational evidence that supports it. This work examines the similarities and differences in these specifications and addresses when cosmology could be taught within a physics course, what should be included in this teaching and in what sequence it should be taught at different levels.

Introduction

Contained within the frameworks of UK National Curricula, the model of the Big Bang is a requisite part of present-day physics teaching (see Pimbblet 2002 for a fuller discussion). For example, the English National Curriculum states that pupils should be taught 'about some ideas used to explain the origin and evolution of the universe'. Building upon these curricula, the major examination boards in the UK incorporate statements about the origins of the universe in their syllabi (see the appendix).

There is, however, little guidance about when to teach cosmology (both within a physics course and at what point in schooling), what topics and issues to cover and in what order to teach them. The plan of this article is as follows. We examine what topics are required to be taught, firstly at GCSE level and then at A-level. Within each of these areas, we define the sequence of topics to be taught. Finally we address when cosmology should be taught within any given physics course.

Throughout our discussion we emphasize an observational approach. This is because any successful cosmological theory (such as the Big Bang) must be able to explain the observations, and secondly, we have found that such an approach will help to deal with many misconceptions that pupils hold (Pimbblet 2002, Prather *et al* 2002).

Cosmology in science courses for 14–16 year-olds

All of the GCSE specifications (see appendix) require an understanding of the Hubble relation. In some cases this is explicit in the form of $v = Hd$; in others it is implicitly suggested via a qualitative relationship between recession velocity and distance (Hubble and Humason 1931). Given that the Hubble relation represents one of the major cornerstones of evidence in favour of an evolving universe, this is of little surprise.

Many of the examination syllabi, however, delve little further into cosmology education than Hubble's relation. It is of credit to Edexcel that its

course goes into a little more depth. Firstly, there is the topic of the future evolution of the universe. Depending on the amount of mass and energy that the universe possesses, one of several fates may befall it. If the universe has enough matter, then it may cease expanding and start to contract under gravitational force. This would result in a 'Big Crunch' scenario. Conversely, with very little matter content, the universe would simply go on expanding forever. The figure of merit that determines which fate awaits the universe is known as the critical density and represents a quantity of matter that is just sufficient to cease the expansion of the universe. Modern observations display a trend in favour of the latter scenario (Perlmutter *et al* 1999). Further, the inflationary scenario (e.g. Guth 2000) provides a theoretical backdrop for constraining the ratio of the actual density to the critical density to be very close to 1 (i.e. the universe just manages to avoid collapsing back in on itself).

Related to this topic is the issue of dark matter. It is thought that much of the matter in the universe has not been (and probably cannot be) observed directly (e.g. Peebles 1993). Therefore, the so-called cold dark matter (e.g. Governato *et al* 2001, Colberg *et al* 2000) will add a significant amount of matter to the content of the universe and hence will influence its future evolution.

The final topic that appears in some GCSE course specifications is the cosmic microwave background radiation, arguably one of the most important astronomical discoveries of the twentieth century (Penzias and Wilson 1965). If interpreted as highly redshifted radiation from the Big Bang, it provides unrivalled evidence for an evolving universe that was once extremely hot—several billion kelvin (see Pimbblet 2002 for further discussion of this point).

Interestingly, the GCSE Edexcel syllabus also makes explicit reference to the 'Steady State' theory of the universe. It is easy, perhaps, to forget that the Big Bang theory was at one time just one of many competing theories (see Ellis 1987 for a review of alternative cosmologies). In 1948 Fred Hoyle and collaborators proposed the rival Steady State theory. In simple terms, this theory describes a universe that is homogeneous, isotropic and isochronal. That is to say, almost the same as the Big Bang model apart from that it appears identical no matter what point in time it is viewed at (i.e. it has no definite beginning). Whilst it can explain an expanding universe, it predicts that there must also be a continuous creation of matter—something that has never sat well with the astronomy community. The fall from grace for the Steady State theory came with the discovery of the cosmic microwave background (Penzias and Wilson 1965, see above), for which only the Big Bang model provides a compelling, natural explanation.

Therefore, within any GCSE course, we advise teachers to commence cosmology with a review of some of the observational evidence in favour of the evolutionary Big Bang model: the Hubble relation and the cosmic microwave background radiation. This can then readily be underscored with a discussion of the future evolution of the universe. Finally a whole-class discussion about other cosmological theories, including the Steady State theory, can take place (Pimbblet 2002).

Cosmology in advanced pre-university courses

The UK A-level specifications (see appendix) broadly follow the same pattern as those developed for GCSE level. They concentrate on the observational foundations of the evolving Big Bang theory (see above) but also touch on other topics.

For example, the OCR specification includes Olbers' paradox. Named after Wilhelm Olbers (1758–1840), the paradox is an old astrophysical issue (see Jaki 1969 for an authoritative summary of pre-twentieth century work). Simply put, the paradox asks why the night sky is so dark. If the universe is of an infinite age and the stars that it contains are distributed evenly (i.e. homogeneous and isotropic), it is fairly straightforward to conclude that the night sky should be equal in brightness to the Sun (e.g. Tipler 1988). Olbers' own resolution to this paradox was to conceive of invisible interstellar dust absorbing the light. Yet, this explanation is insufficient: the amount of dust required would obscure the Sun during the day! Work that followed demonstrated that in order for the night sky to appear luminous, the universe must possess an age of 10^{23} years. Therefore, the assumption of an infinite age for the universe is invalid. Yet, authors also overlooked two important factors for some time: stars have finite

ages (hence they burn out) and *special* relativity (hence each photon of light that arrives carries less energy than when it was emitted). Whilst Harrison (1987) shows that the dominant factor is the finite ages of stars, both effects contribute in the same way: to make the sky darker and thus resolve the paradox.

One major part of cosmology that is conspicuous by its absence from A-level is the abundance of the elements that results from nucleosynthesis (e.g. Burles *et al* 2001). In simple terms, Big Bang nucleosynthesis explains why there is an abundance of light elements in comparison to heavier elements. As such, it provides cosmologists with a very good method of testing the quantitative predictions of Big Bang theory (Krauss and Romanelli 1990). We advocate that teachers include nucleosynthesis in any advanced level course because, taken in combination with the Hubble relation and the cosmic microwave background radiation, it makes the Big Bang theory appear highly watertight.

Finally, although not on any examination syllabus examined, there are further pieces of observational evidence pointing towards an evolving (and hence non-steady state) universe. Such evidence should only be taught to high ability classes when time permits. For example, the Butcher–Oemler effect (Butcher and Oemler 1984) shows a recent, strong evolution within the stellar populations of galaxies. This effect demonstrates that the fraction of blue, star-forming (young) galaxies within clusters of galaxies increases with increasing redshift (and hence with decreasing time since the Big Bang). Thus, clusters of galaxies that are further away are less evolved and younger than those located nearby.

Therefore, any advanced level course should broadly follow the sequence outlined for GCSE courses. We advise teachers to build upon the observational evidence in favour of the Big Bang theory: the Hubble relation, cosmic microwave background radiation and include nucleosynthesis. Olbers' paradox can potentially be slotted in after this, or at the end of teaching about stellar evolution. As time permits, other bits of evidence such as the Butcher–Oemler effect can also be included as evidence in favour of the Big Bang. The sequence would then follow the GCSE outline again: the future evolution of the universe and a guided class discussion about alternative cosmologies.

Sequencing cosmology education

Having outlined what topics to teach and in which order to teach them, we now turn to the question of when cosmology should be taught within a given physics specification.

Astrophysics as a discrete unit of teaching typically comes last within any GCSE or A-level scheme of work. Since the topic requires a synthesis of prior knowledge from many parts of a syllabus, this can provide useful revision. The downside is, of course, that teachers will probably not leave sufficient time for it. Attempting to teach this topic earlier, say at the beginning of the final year of a course, may prove productive, especially given its timeless popularity (e.g. Toscano 2002). Instead of being a synthesis for other topics, astrophysics can readily be turned into a springboard for them. Thus we advocate teaching astrophysics in the middle of a physics course, after some groundwork in classical physics such as forces.

Within astrophysics, cosmology nearly always comes last. The reason for this appears to be that astrophysics is taught lengthwise as a 'bottom-up' subject: starting off with Earth-bound phenomena and working up in scale through the solar system to the universe as a whole. The bottom-up method is, however, a sound premise because it institutes in pupils a sense of the scale of the universe.

Conclusions

This work has discussed an appropriate sequence for teaching cosmology (within both the 14–16 year-old age range and in pre-university courses), what topics to include and at what point in schooling it should be taught.

We have suggested that:

1. Astrophysics as a discrete unit should be taught in the middle of a course once sufficient grounding in classical physics (e.g. forces) is completed. It can then be used as a springboard into other topics (e.g. light).
2. Cosmology should be the last subject within an astrophysics unit.
3. Cosmology education should be built upon the observational foundations that support the Big Bang theory (Hubble's relation and the cosmic microwave background radiation at GCSE with the addition of nucleosynthesis

Table 1. These are the results from surveying the major examination boards' syllabi for cosmology education content. Each syllabus is analysed for content and this is presented in the 'Categories' column.

      H: denotes reference to Hubble's relation, either implicitly or explicitly;
      μ: denotes reference to the cosmic microwave background radiation;
      Ω: denotes reference to the future evolution of the universe;
     DM: denotes explicit reference to dark matter;
 Olbers: denotes reference to Olbers' paradox.

Examination board, type and year	Exemplar statement	Categories
CCEA GCSE Physics (2004)	Describe the big bang model for the creation of the universe	H
AQA GCSE Physics (2003)	. . . This suggests that the whole universe is expanding and that it might have started, billions of years ago, from one place with a huge explosion ('Big Bang')	H
Edexcel GCSE Astronomy (2003)	Describe the Big Bang theory of the origin of the universe and consider other theories such as the 'steady state' theory. Explain how the future of the universe depends on the amount of mass present	H, μ, Ω, DM
OCR GCSE Physics (2003)	Interpret given information about developments in ideas on the origin of the universe	H, Ω
WJEC GCSE Physics (2003)	Understand that these ideas support a model of an expanding universe which originated approximately 12 billion years ago with the Big Bang	H
AQA A-level Physics (2003)	(Hubble's law) . . . Qualitative treatment of Big Bang theory	H
OCR A-level Physics (2003)	Describe qualitatively the evolution of the universe from 0.01 s after the Big Bang to the present. . .	H, μ, Ω, Olbers

Note that the AQA specification suggested that the universe started from one *place*. This is a common misconception. From Einstein's field equations of general relativity (e.g. Einstein 1950), it is known that $G_{\mu\nu} = 8\pi G c^{-4} T_{\mu\nu}$. For a flat space-time, the $G_{\mu\nu}$ components will vanish. They will also vanish for an absence of matter and pressure. The startling bottom line is that space-time is generated by matter itself. Therefore, to say that the universe started from one place is simply wrong: with no matter, there could not have been any 'place', anywhere, to define! It is gratifying to see that AQA have deleted the phrase 'from one place' for their 2004 GCSE syllabus.

at A-level). Any successful cosmology must, after all, be able to explain such observations.
4. Both Olbers' paradox and the Butcher–Oemler effect broadly support the case for an evolving universe and can be taught at Advanced level.
5. A discussion about the future evolution of the universe and other cosmologies (Pimbblet 2002) should then follow.

This work follows Pimbblet (2002) and is the second paper in a series examining aspects of cosmology education.

Appendix

Table 1 provides a brief survey of examination syllabi from the major examination boards in England, Northern Ireland and Wales. (Scotland has been excluded from this survey simply because its examination structure is so different from that of the rest of the UK.) The contents of non-UK physics course specifications are broadly similar in nature regarding cosmology. Readers from outside the UK may be surprised at the knowledge expected of students for GCSE level (age 14–16) and A-level (age 16–19), especially considering the already heavily loaded teaching schedule (Thomas 2002). Cosmology is typically only taught to students who are expected to achieve the higher grades (C or above at GCSE level) and

is usually not required in foundation level GCSE physics courses.

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