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RESEARCH REPORT

Big Ideas: A review of astronomy education research 1974–2008

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This paper reviews astronomy education research carried out among school students, teachers, and museum visitors over a 35-year period from 1974 until 2008. One hundred and three peer-reviewed journal articles were examined, the majority of whose research dealt with conceptions of astronomical phenomena with 40% investigating intervention activities. We used a conceptual framework of "big ideas" in astronomy, five of which accounted for over 80% of the studies: conceptions of the Earth, gravity, the day–night cycle, the seasons, and the Earth–Sun–Moon system. Most of the remaining studies were of stars, the solar system, and the concepts of size and distance. The findings of the review have implications for the future teaching of, and research in, the discipline. Conceptions of the Earth and the day–night cycle are relatively well-understood, especially by older students, while the Moon phases, the seasons, and gravity are concepts that most people find difficult both to understand and explain. Thoroughly planned interventions are likely to be the most effective way of implementing conceptual change, and such studies have been well-researched in the past 15 years. Much of this recent research has worked with constructivist theories resulting in methodological and theoretical insights of value to researchers and practitioners in the field. It is recommended that future research should work across the disciplinary boundaries of astronomy education at school and teacher education levels, and aim to disseminate findings more effectively within the education systems.

Keywords: *Astronomy Education Review; Big ideas; Earth; Moon; Seasons; Solar system; Star*

Introduction

Aspects of astronomy have been popular topics in school curricula for decades. In the lower primary school, themes such as "space" or "the planets" have been used

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by teachers to inspire and fascinate students in much the same way as dinosaurs have captivated small children. Most cultures have a variety of stories to explain the events we see in the sky everyday. A paradox is that some of the most readily experienced phenomena such as day and night, the phases of the Moon, and the seasons can only be understood using complex and non-intuitive explanations. For example, a common way to account for seasons is to invoke the Earth's varying distance from the Sun throughout the year, yet the real reason involves a combination of the Earth's orbit, tilt and its spherical nature.

Educational research over the last century has investigated a wide variety of aspects of how people understand astronomical phenomena, from young children's naïve explanations of the Sun's movement to the most effective ways to teach gravitational force in the solar system. As early as the 1920s, Jean Piaget made the first scholarly studies of how children conceive of astronomical phenomena. In his two books, *The child's conception of the World* and *The child's conception of physical causality*, he describes children's ideas about a flat Earth and the cause of day and night, and refers to previous psychologists' work on similar conceptions (Piaget, 1929, 1930). Piaget's work has been influential for decades, and has helped to shape our understanding of how the non-intuitive phenomena around us can be explained, particularly prior to instruction on the topic.

Within science education, reviews of research have followed different formats (Lubben, 2009), for example narrative reviews which examine a topic globally or regionally, and systematic reviews in which strategies for teaching are examined. In 1973 Wall published a review of research related to astronomy education dealing with the 50-year period to 1972 (Wall, 1973). Since then there have been five reviews of various aspects of astronomy education research, three of which have examined astronomy education globally (Adams & Slater, 2000; Bailey, Prather, & Slater, 2004; Bailey & Slater, 2004). However, all three of these reviews were limited in scope, included research presented at conferences in addition to peer-reviewed journals, and were published in specialist journals. The other two reviews examined specific topics: the Earth in space (Albanese, Danhoni Neves, & Vicentini, 1997) and research at planetaria (Riordan, 1991). In contrast, the present paper is rigorous in its selection of research articles examined, is comprehensive and targets the wider science education community within the schooling and teacher education research sectors.

Several texts (e.g. Adams & Slater, 2000; Stahly, Krockover, & Shepardson, 1999) refer to the scarcity of research in astronomy education. We disagree that this is the case, and have identified a considerable increase in peer-reviewed journal articles since the early 1990s (Figure 1). In the past three decades, hundreds of studies have examined people's conceptions of astronomy, and how their understandings can be moved towards more scientific notions. The key questions we ask in this paper are the following:

- How has the research into astronomy education furthered our understanding of learning about aspects of astronomy?
- What methodologies and theoretical frameworks have researchers used to understand astronomy learning?

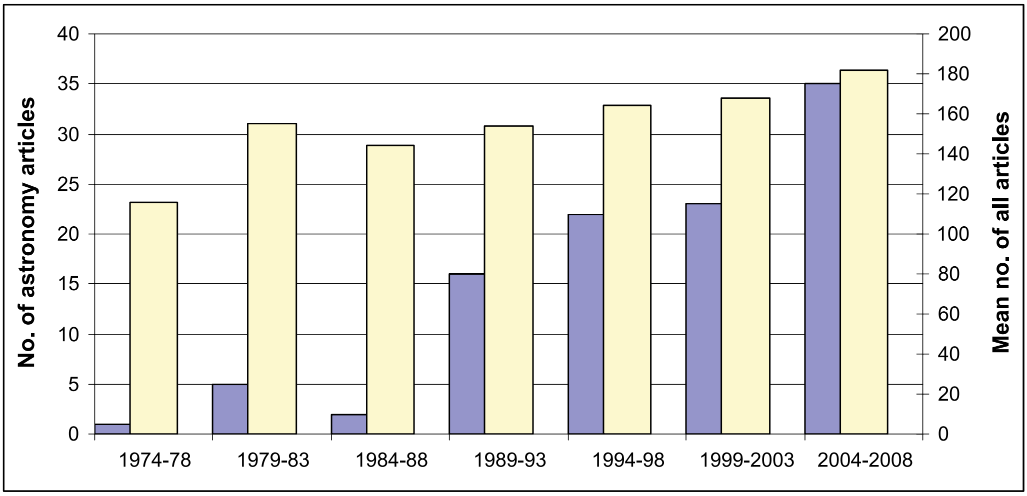

Figure 1. Astronomy articles (shaded) selected for this review (n=103) by year of publication plotted against mean number of articles published per annum in three leading science education journals over the review period

- What should be the future agenda both for astronomy education and research in the field?

Method and Sources of Data

Ours is a narrative review (Jones, 2004) in which we used qualitative methods to synthesise new interpretations across a range of studies. The primary methods were to treat the different research studies as cases, compare them with each other, and come up with new interpretations for the field rather than making "trite conclusions" (Noblit & Hare, 1988, p. 28).

In order to answer our research questions, we first sought a suitable conceptual framework for the study to amplify the data obtained. We developed a set of categories of learning using the notion of "big ideas" to define key concepts in basic astronomy. The notion of "big ideas" comes from the American Association for the Advancement of Science's (AAAS) Project 2061 which developed "topics of importance" for literacy in science, mathematics, and technology. The Project 2061 developers map out different aspects of science with the intention of providing a series of strand maps which educators such as teachers and curriculum developers can use to locate the benchmarks for science literacy within the curriculum. Instead of the term "theme" or "topic" the AAAS has started informally using the term "big idea" (AAAS, 2005), a notion which we find useful to identify key concepts for our study. Big ideas have also been used by Loughran and colleagues in their development of teachers' Pedagogical Content Knowledge (PCK) (Loughran, Mulhall, & Berry, 2004). Lelliott (2007) identified a number of big ideas based on the strand maps of the AAAS cluster "The Universe" reflecting key concepts in astronomy. In this paper we use eight big ideas to structure our discussion of the research studies reported below. Four of these topics (gravity, the solar system, stars, and the concepts of size and distance) can be regarded as big ideas fundamental to the science of astronomy. The remaining four big ideas (Earth shape, the day/night cycle, the seasons, and the Earth/Sun/Moon system) represent topics commonly taught at school level, and intensively researched over the past 30 years.

We then developed criteria for selection of the literature. These are shown in Table 1.

In view of its comprehensive listing of journal articles, we conducted a search of the Education Resources Information Center (ERIC) database using the keywords

Table 1. Criteria for selection of the articles

Criterion	Justification
Research papers in which astronomy is the focus of the study, based on the big ideas described above.	Astronomy education is the subject of the review and the notion of big ideas is the framework by which we have structured the article. Studies of physical phenomena not specifically related to astronomy (e.g. gravitational experiments in the classroom) have been excluded to maintain the focus.
Studies conducted in primary and secondary classrooms, during visits to museums and science centres, and among pre- and in-service teachers.	Schooling is the first time children are provided with scientific explanations of astronomy concepts. Teachers' knowledge of the subject is key.
Post-secondary courses (e.g. university level courses) are not included, with the exception of teacher education.	They are not associated with the schooling sector.
Research articles published between the years 1974 and 2008.	Charles Wall's review related to astronomy education dealing with the 50-year period prior to 1972 (Wall, 1973). The subsequent 35 years of research is an appropriate period in which to identify the main themes and to detect trends and changes of emphasis.
Only peer-reviewed print-based journal articles.	These have been subject to a degree of quality control, ensuring greater rigour and trust in their findings. The only exception to this was to include articles from *Astronomy Education Review*, an online journal devoted to research into the teaching of astronomy, on the grounds that it is a recent and highly relevant journal, and its exclusion would result in the omission of useful articles.
Empirical studies, conceptual pieces, and reviews from the full range of research methodologies, but excluding historical analyses, practitioner, and opinion pieces.	In order to limit the scope of the review to exclude the vast literature of "how to teach" advice.

Note. Worldwide in English.

"astronomy", "education", "learning", and "teaching". The ERIC search (limited by publication type and education level) revealed 550 articles with the keywords astronomy and education, 125 studies with the keywords astronomy and learning, and 163 studies with the keywords astronomy and teaching. Google Scholar has fewer search-limiting functions, and identified over 900 articles when the terms astronomy and education were present in the title. Using the ERIC searches, we read the abstract of each article and on the basis of the criteria described above decided whether or not to include it in the review. While the majority of studies from these searches fulfilled our first four criteria most were ultimately excluded as they were either not peer-reviewed or consisted of "tips for teachers" or descriptions of teaching programmes. We also conducted a manual search of the leading science education journals, notably the *International Journal of Science Education*, the *International Journal of Science and Mathematics Education*, the *Journal of Research in Science Teaching*, *Research in Science Education*, *Research in Science and Technological Education*, *Science Education*, *Studies in Science Education*, and *Science and Education*. We scrutinised the reference lists of all articles examined to identify additional studies not located by the other methods.

An Analysis of the Literature Base

The selection process for identifying relevant literature described above resulted in a total of 103 articles which are discussed here and summarised in Figures 1–3 and Tables 1–3.

Figure 1 shows that for the first 15 years of the review period, only eight articles were published, while the remaining 95 have been published since 1991, increasing every five-year period. This trend suggests greatly increased interest in the subject of astronomy education since 1990, reflecting a growing attention paid to it in school and teacher education curricula (e.g. AAAS, 1993). This is substantiated by researchers, such as Baxter (1991) and Jarman and McAleese (1996) in the UK, Trumper (2001a) in Israel, and Stahly et al. (1999) in the USA, who acknowledge the introduction of astronomy topics into revised curricula in the late 1980s and 1990s. Nearly a quarter of the articles were published in the *International Journal of Science Education*, while *Science Educatio*n and the *Journal of Research in Science Teaching* together account for a further quarter. The remaining 56 articles are found in a variety of educational journals, mainly (but not exclusively) based in Europe and the USA. An examination of the mean number of science education articles published in the three named journals shows that while there is a general increase in the number of articles published over the review period, there is no abrupt increase in the 1990s as in the case of astronomy education articles. There can be no doubt that the numbers attest to the increased significance attached to astronomy in education.

Classifying the methodologies used by the researchers into "quantitative" and "qualitative" research designs proved somewhat of a challenge, as several of the studies used designs which were difficult to interpret. However, we devised five categories across the range of studies (Table 2). In the quantitative categories, survey research aimed at measuring the astronomy knowledge of a large number of

Table 2. Research designs used by the research studies during the review period (n=103)

Research design categories	Number of studies
Qualitative study only	32
Quantitative survey	22
Qualitative study, with intervention	16
Quantitative intervention	14
Quantitative and qualitative intervention	10
Other	9

Table 3. Big ideas investigated by researchers over the review period (37 studies included more than one topic)

Big idea	Number of studies
Earth conception	38
Gravity	25
Day and night	35
Seasons	27
Earth–Sun–Moon system	36
Solar system	13
Stars and Sun	14
Size and scale	9
Other	7

participants and intervention research (often quasi-experimental) aimed to determine the effectiveness of a teaching approach or method. The qualitative categories consisted of non-intervention studies (e.g. case studies and small-scale investigations) and intervention studies (e.g. teaching–learning sequences). Seven studies explicitly used mixed-methods approaches across the qualitative and quantitative paradigms. A clear trend over time has been the increasing number of intervention studies since the mid-1990s (prior to 1997 there were only two), and the detail in which the interventions are now described (particularly since 2003). While several studies longitudinally collected data over a period of months, only three studies exceeded one year. The great majority of studies collected data from students based at their schools, while 21 studies involved teachers, and seven collected data in a museum or science centre (e.g. planetarium).

Like methodologies, theoretical frameworks adopted by the researchers were difficult to classify, as most authors did not specify the theoretical basis of their research. In a quarter of the articles more than one theoretical framework was evident, and we identified four principal frameworks across the field as follows (see Figure 2):

- Conceptions held by study participants, normally associated with individual or personal constructivism and in some cases relating to Piaget's developmental theories (Bliss, 1995; Duit & Treagust, 1998).

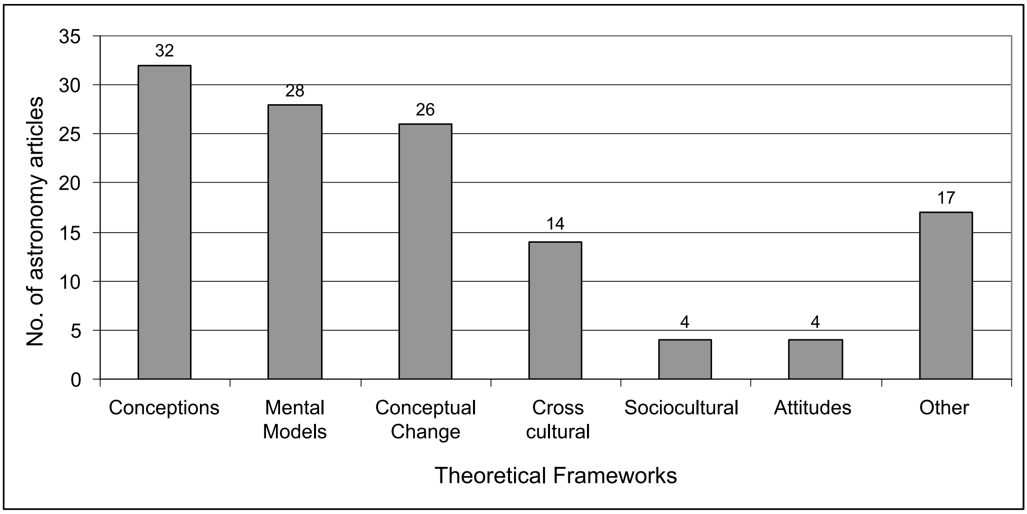

Figure 2. Theoretical frameworks used in research studies during the review period (24 studies used more than one framework)

- Mental models or frameworks of conceptions held by participants (e.g. Vosniadou & Brewer, 1992, 1994).
- Studies of conceptual change and knowledge acquisition (Hewson & Hewson, 1992; Strike & Posner, 1985).
- Cultural, cross-cultural, and worldview studies (e.g. Diakidoy, Vosniadou, & Hawks, 1997; Fleer, 1997).

Less frequently occurring frameworks included sociocultural theories (e.g. Engeström, 1991) and attitudes (e.g. Jarvis & Pell, 2005), while the theories used least were combined into a category "Other" which included PCK, modelling, and humour.

Nearly two-thirds of the studies examined more than one big idea within astronomy, rather than investigating a single topic in depth. Table 3 shows the variety and frequency of big ideas investigated.

Five big ideas within astronomy have been the most intensively studied, all involving the Earth in relation to its satellite and the Sun. From the early studies by Nussbaum (Nussbaum, 1979; Nussbaum & Novak, 1976) to recent studies by Sharp and Sharp (2007) and Hannust and Kikas (2007), 38 studies have included students' conceptions of the Earth's shape as a commonly researched topic. The second most frequently researched topic involves the Earth–Sun–Moon system (36 articles), closely followed by research into the day/night cycle (35 articles). The big ideas of "the seasons" and "gravity" account for 27 and 25 studies, respectively, while considerably less research has been carried out on the big ideas of the stars and Sun (14), the solar system (13), the concepts of size and distance (9), and cosmology (3) despite their relevance to modern astronomy. The majority of research investigated several big ideas within one study, while about one-third focused on one big idea only.

There are a few key studies which have had considerable influence on subsequent research, and these were identified by the number of citations shown for each study in Google Scholar. Using a benchmark of 100 citations, Vosniadou's work is the most influential in the field, with Vosniadou and Brewer (1992, 1994) achieving 524 and 195 citations, respectively. These are followed by Nussbaum's work, with Nussbaum and Novak (1976) and Nussbaum (1979) attaining 192 and 149 citations, respectively. Finally, Baxter (1989) had 152 and Engeström (1991) 119 citations. Although older works (such as Nussbaum's) might be expected to have the higher number of citations as more time has elapsed since the studies were published, it is clear that Vosniadou's studies have had an enormous influence on later research; this influence is discussed in the sections below. There are also more recent studies which have not yet been cited extensively, but are likely to influence future research, and are discussed in subsequent sections. These include Sharp's work over the past 10 years (e.g. Sharp, 1999; Sharp & Kuerbis, 2006; Sharp & Sharp, 2007), the longitudinal studies of Bryce and Blown (Blown & Bryce, 2006; Bryce & Blown, 2006) and further work examining mental models (e.g. Taylor, Barker, & Jones, 2003).

Before we examine the big ideas in astronomy education, it is worth briefly looking at how attitudes towards astronomy (and science) have been approached by researchers, as they have received some attention in recent years (e.g. Jenkins, 2006; Osborne, Simon, & Collins, 2003). Four studies, all principally quantitative, are of interest in our paper, as they relate directly to astronomy. The first (Jarman & McAleese, 1996) surveyed about 3000 15-year-olds in the UK as they entered key stage 4, and again at the end of the year. To the researchers' surprise, astronomy scored highest across both groups when compared with the other sciences. During subsequent interviews with a sample of the pupils, the researchers found that the "remoteness", "unknownness", and excitement of discovery all contributed to the level of interest. Jarman and McAleese (1996) concluded that "there seems to be something inherent in the subject of astronomy itself which appeals to many of our young people" (p. 225). Two other studies examine attitudes towards science and space, and were conducted as the result of a visit to the National Space Centre (Leicester, UK). The first study (Jarvis & Pell, 2002) found that a visit to the innovative Challenger Experience, in which 655 10- and 11-year-olds took part in a simulated space trip to rendezvous with a comet had varying effects on the children. A quarter of them were inspired by the visit to become scientists, showed greater science enthusiasm and maintained this positive attitude for several months. A further quarter, who were already interested in science, "were less affected by the experience" (p. 996), while the remaining half showed even less change in their attitude or developed negative perceptions. A follow-up study of 300 children of the same age range (Jarvis & Pell, 2005) showed that the experiences at the Challenger Experience and the general exhibition area resulted in positive short-term gains in interest about space and the value of science in society. Finally, a recent case study in which trainee teachers conducted project work using robotic telescopes found high levels of enthusiasm in both the use of the software and the authentic tasks they were carrying out (Beare, 2007).

The following sections synthesise the research carried out, demonstrating what has been revealed over the 35-year period under review.

Research Synthesis Based on Big Ideas in Astronomy

Conceptions of the Earth

The scientifically accepted view of the Earth is that it is nearly spherical and surrounded by space. Living organisms are found all over its surface and are held there by gravity, which causes things to fall towards the Earth's centre.

Of the 38 studies of this big idea, 19 were dedicated to Earth shape and gravity only (working exclusively with younger children aged 7–14), while the remainder included other big ideas in astronomy. Unlike the other big ideas, none of the Earth conception studies involved teachers, probably because notions of Earth shape and gravity appear to be well-developed by the time people reach their teenage years. Drawing on the early work by Nussbaum and Novak (1976), all but two of the studies used interviews to collect their data and the majority used models, supplemented in some cases by drawings and/or written questions.

The seminal study by Nussbaum and Novak (1976) was the inspiration for several subsequent articles, including those of Nussbaum (1979), Mali and Howe (1979), Klein (1982), Sneider and Pulos (1983), and Baxter (1989). The research was carried out from a cognitive perspective and demonstrated that children have five notions of the Earth, which appear to be developmental in nature, although the studies were all cross-sectional rather than longitudinal. At earlier ages (mainly 7–9 years) children have an egocentric "flat Earth" notion which develops as they are exposed to scientific ideas (Figure 3).

By the 1990s, some researchers took a more theoretical view of children's conceptions. For example Vosniadou and colleagues proposed that children hold "mental models" of the Earth's shape and gravity. Drawing on earlier work (Vosniadou, 1991), Vosniadou and Brewer (1992) proposed that previous studies lacked rigour in that the criteria for defining notions were not explicit, and that the studies did not determine whether children used notions in a consistent manner. Using a rigorous scoring guide and looking for consistency in children's answers, Vosniadou and Brewer worked with 60 children aged from 6 to 11 years. They classified their models into three categories: intuitive (egocentric, derived from direct experience), scientific (the currently accepted scientific view), and synthetic (a combination of intuitive and scientific). Vosniadou's work has been immensely influential since the early 1990s. Subsequent studies including those by Sharp (1996), Diakidoy et al. (1997), Roald and Mikalsen (2000), Diakidoy and Kendeou (2001), Kikas (2005), Liu (2005), Vosniadou, Skopeliti, and Ikospenkati (2005), Cin (2007), and Hannust and Kikas (2007) all examined children's mental models

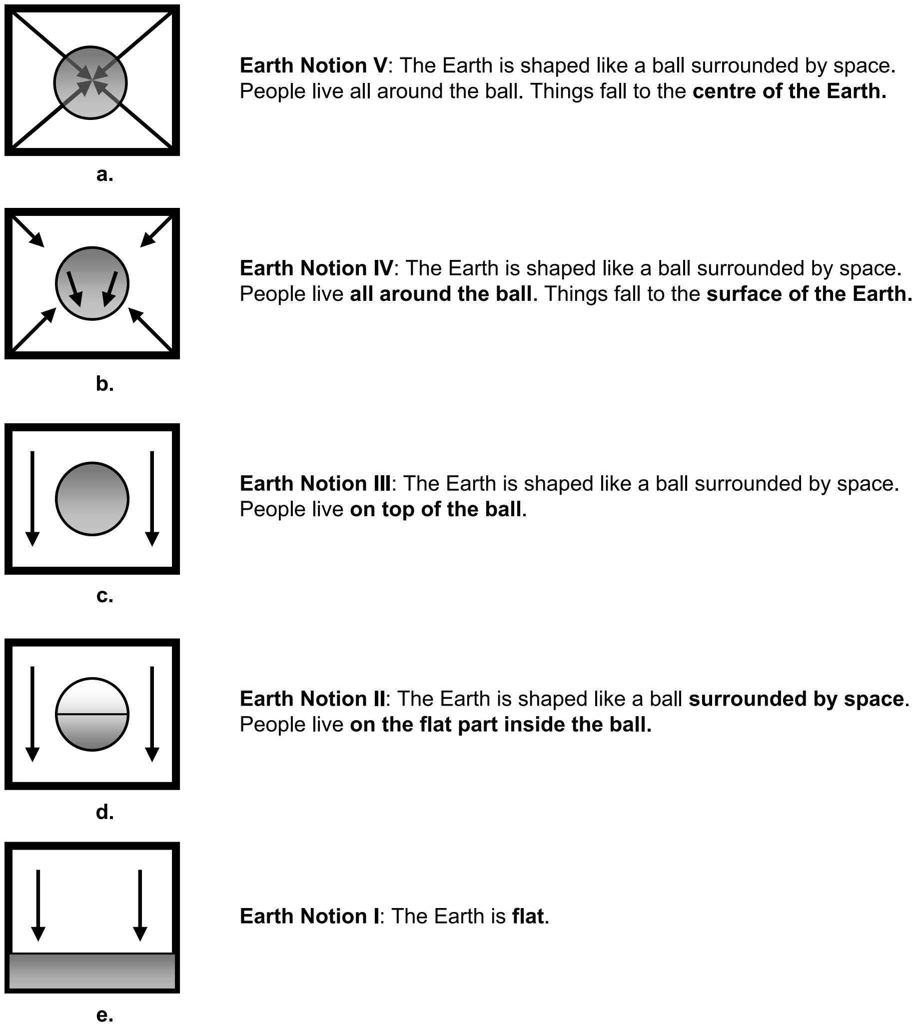

Figure 3. Earth notions classification scheme. After Sneider and Pulos (1983)

of the Earth, in some cases combined with instructional methods, and tended to confirm Vosniadou's theory. Other studies have critiqued the theory. For example a paper by Schoultz, Säljö, and Wyndhamn (2001) criticises Vosniadou and her associates for failing to use a globe when questioning children about the Earth and gravity. Using a situated and discursive framework, Schoultz et al. (2001) claim that the introduction of a globe to an interview results in substantially different responses from children (ages 7–11) than in the Vosniadou study in which the children had to think abstractly. Another study (Nobes et al., 2003) suggests that Vosniadou's analysis is a "circular process" in which "there is a danger of 'finding' consistency—and … mental models—when in reality there is none" (p. 83). In their rigorous and extensive longitudinal study of Chinese and New Zealand children Bryce and Blown (2006) attempt to end this debate by advising researchers that "there is a need for modesty when reflecting on one's findings in comparison with others" (p. 1144). Their study stresses that researchers need to design their instruments very carefully, particularly when making cross-cultural comparisons. Blown and Bryce's (2006) articles also suggest that Vosniadou's cultural mediation theory is not the main way that children acquire astronomical concepts, but instead "children's cosmologies gradually develop towards the scientific view" by cognitive processes of meaning making (p. 1457). In a quasi-experimental study, Sharp and Sharp (2007) came to similar conclusions and suggested that the various theoretical positions on knowledge acquisition represent a learning continuum rather than unrelated constructs.

Gravity

Within the context of basic astronomy, gravity is a force of attraction between bodies and is directly proportional to the product of the masses of the objects and inversely proportional to the square of the distance between bodies (Newton's universal law of gravitation). It is often covered at schools as a rather dry topic within the theme "mechanics", and as a result, students' understanding of gravity in relation to the Earth and the solar system is usually limited to solving calculations and exam-style problems.

The majority of the 25 studies of gravity also included aspects of the Earth's shape described above. A particular difficulty in selecting articles on gravity was the fact that many were combined with "mechanics" studies in the laboratory or classroom which involved weight and "falling body" experiments (e.g. McDermott, 1984; Watts, 1982; Watts & Zylberstajn, 1981). For this review, we focused on studies of the understanding of gravity as a big idea with respect to astronomy, 80% of which were published during the last two decades. All of the studies used written questions and/or interviews rather than multiple-choice questions, and half of studies used models as part of the interview process.

Noce, Torosantucci, and Vicentini (1988) used a combination of a paper-and-pencil test and interviews to identify Italian students' and teachers' conceptions of gravity on the Moon and in the laboratory. They found that the majority of the younger students (aged 9–10) believed that objects float on the Moon, and that air is necessary for gravity to act. The older students (16–18 years) had a geocentric notion of gravity, and did not relate it to the atmosphere, while the Newtonian explanation for gravity was minimal across all ages. These findings were supported by studies in Australia (Treagust & Smith, 1989), Canada (Berg & Brewer, 1991), Mexico (Reynoso, Fierro, Torres, Vicentini-Missoni, & Perez de Celis, 1993) and the USA (Borun, Massey, & Lutter, 1993). All such studies show a large number of alternative conceptions about gravity, such as its need for an atmosphere to cause an effect, and its absence from space. As in other big ideas, teachers, especially those at primary level, possess many of the alternative conceptions about gravity held by their students (e.g. Reynoso et al., 1993), and are unaware of the conceptions their students hold (e.g. Berg & Brewer, 1991). Consonant with constructivist views of alternative conceptions, most of the studies recommended teaching interventions which involve confronting students' beliefs and ideas about gravity (e.g. Bar, Sneider, & Martimbeau, 1997), rather than expository and drill-and-practice methods often used in classrooms.

Although based on alternative conception research, the study by Borun et al. (1993) tried an interesting variation. In a museum environment, they determined visitors' alternative conceptions about gravity, and then tested the efficacy of hands-on exhibits in changing those conceptions. Using the notion of "novice" and "expert" visitor, the study claimed that the intervention changed visitors' notions of what gravity is *not*, rather than imparting a true scientific concept. Borun's study was critiqued by Feher (1993) and Falk and Dierking (2000), who maintain that single exhibits are unlikely to change visitors' understanding of gravity because their alternative conceptions are complex and deeply ingrained. Instead, by using "networks of exhibits", visitors can make better connections for themselves and "reorganise their ideas and construct new understandings" (Feher, 1993, p. 247).

Day/Night Cycle

The basic scientific explanation for how day and night occur is that the Earth spins on its axis, completing a turn once every 24 hours. The side facing the Sun experiences day, while it is night on the other side.

Of the 35 studies of the day/night cycle, only three were dedicated solely to this big idea, while the remaining 32 included one or more other topics. Five of the studies involved teachers, while the remainder concentrated mainly on primary school children with a few studies (10) including older students. Over half of the studies used interviews as their principal or only data collection method, while 13 used models explicitly.

The early studies in our review period such as Klein (1982), Jones, Lynch, and Reesink (1987) and Baxter (1989) found that younger children held naïve views in explaining why the cycle occurs, such as using hills and clouds. Older children were more likely to provide explanations which use astronomical objects, although they were not necessarily scientifically correct. Vosniadou offered a theoretical basis for children's explanations by using a similar mental model theory as she had developed for conceptions of the Earth (Vosniadou, 1991; Vosniadou & Brewer, 1994). She predicted that (and found empirical evidence to support) children's conceptions could be classified into intuitive, synthetic, and scientific models. Vosniadou's research (Diakidoy et al., 1997; Vosniadou & Brewer, 1992) has influenced several subsequent researchers, who have used her notion of mental models to examine not only the day/night cycle but other aspects of astronomy understanding, such as the solar system and the Moon phases (e.g. Liu, 2005; Roald & Mikalsen, 2001; Sharp, 1996). These subsequent studies show the prevalence of synthetic models of the Earth–Sun–Moon system among primary and junior secondary students, though the majority could explain day and night in terms of the Earth's spin. Fleer (1997), in a study of four- to eight-year-old rural aboriginal children in Australia, confirmed

Baxter's and Vosniadou's findings for young children, with additional beliefs from the aboriginal culture. Both Baxter and Vosniadou suggest that children's mental model development mirrors the discoveries about heavenly bodies made by scientists over the centuries, but other researchers have found no evidence for this (e.g. Roald & Mikalsen, 2001). As we discussed above, Blown and Bryce's (2006) longitudinal studies (which included the day/night cycle) suggest that knowledge restructuring occurs in phases, and is not necessarily mediated by culture.

Other studies (Sadler, 1998; Schoon, 1992; Trumper, 2001a, 2001b) have found that in older children the majority are able to provide a scientific explanation of the day/night cycle. In a Greek study of conceptual change, Bakas and Mikropoulos (2003) found that 52% of their sample (n = 102) gave a scientific explanation, while 100% of the intervention group (n = 27) were able to do so after completing a three-dimensional computer-aided package. Dove (2002) showed that in a science exam in the UK, 91% (n = 98) could explain day and night correctly, and suggested that since only the Sun and the Earth are involved, students understand the concept relatively easily. In a longitudinal study Kikas (1998a) showed contrary results, where 14-year-olds showed less scientific understanding than they had when they were 10 years old. However, she attributed this to the "rote learning" nature of Estonian schooling, and it provides a salutary reminder that mere memorisation of the phenomenon is unlikely to lead to true understanding.

Studies involving UK teachers' understanding of the day/night cycle demonstrated that over two-thirds of the participants could explain the phenomenon scientifically (Mant & Summers, 1993; Summers & Mant, 1995). A similar study by Parker and Heywood (1998) showed that nearly 90% of a sample of practising primary teachers (n = 17) understood day and night scientifically, while primary teachers in training were less science-oriented in their explanations (46%, n = 72). Atwood and Atwood (1995) also showed the importance of the use of physical models when interviewing people about astronomical ideas. Twice as many teachers were able to explain day and night scientifically when manipulating models as when they were providing an explanation in writing. This finding is confirmed for all big ideas throughout our review, and has considerable implications for future research.

The Seasons

Scientifically, the cause of the seasons on the Earth can be explained by four key concepts: the annual orbit of the Earth around the Sun, the 23.5° tilt of the Earth with respect to its orbit, the Earth's spherical nature, and consequent changes in intensity of the Sun's radiation reaching the surface due to the tilt and orbit.

Of the 27 studies which examined people's understanding of the seasons, 21 of them studied other astronomy topics such as the day/night cycle and the Moon. Seven of the studies were carried out with teachers, while the remainder involved school students. Among students, the main finding was that although the concept only involves two bodies, the Earth and the Sun, the non-intuitive explanation of tilt and the Sun's energy falling on a curved surface means that students find it a very difficult phenomenon to explain scientifically. Half of the articles used interviews as a method of data collection, but only eight used models.

Qualitative studies such as those by Baxter (1989), Dunlop (2000), and Roald and Mikalson (2001) found that although students could refer to the Earth's tilt as part of the reason for seasons, a more detailed explanation was not forthcoming. Almost all studies identified the "distance theory" alternative conception, which explains seasons by the Earth being further from the Sun during winter, and closer during summer. Some studies (e.g. Kikas, 1998b; Tsai & Chang, 2005) suggest that students tend to revert to the distance theory after they have forgotten the scientific explanation, demonstrating that their scientific understanding is weakly held. Kikas (1998b) hypothesises that the distance theory is an "everyday" explanation derived from the students' experience of heat sources, as well as misinterpretation of textbook diagrams. However, we consider that her research methods tended to reinforce the notion of orbit around the Sun as the key concept of the seasons phenomenon rather than including tilt and sphericity, and this may have biased her results somewhat. Both Kikas (1998a) and Bakas and Mikropoulos (2003) found results similar to their examination of the day/night cycle described above.

The more quantitative studies used students' answers to one or more questions to determine whether they understood the scientific concept or had alternative conceptions. Most of these studies (e.g. Sadler, 1998; Schoon, 1992; Trumper, 2001a, 2001b) found that few students could properly explain the seasons in their multiple-choice answers, and that the distance theory was often the most common item chosen. Tsai and Chang's (2005) quasi-experimental study showed that constructivist teaching which engaged with students' cognitive conflict elicited a longer retention of scientific concepts than traditional teaching.

Studies investigating teachers' conceptions of seasons identified similar explanations to those of students, with distance theory being the main alternative conception. Ojala's (1992) research, which strangely has been cited by only one subsequent teacher study, found that only five out of 87 participants could correctly explain seasons in terms of the Earth's sphericity (which he regarded as the scientific explanation), while 28 referred to the angle of inclination but could not explain it fully. Mant and Summers's (1993) excellent qualitative study found that some teachers regarded the tilt as causing parts of the Earth to be physically closer or further from the Sun, and therefore identified this alternative conception as being another form of distance theory. The authors also found that many of their teachers "were confused and struggling with contradictions" (p. 114), suggesting an awareness of their own ignorance. Their subsequent investigation (Summers & Mant, 1995) used results from their 1993 study to construct a questionnaire which they used with 120 primary teachers. They found that 83% of the participants chose distance theory to explain the seasons, but some confusing items in the instrument (e.g. "The Earth moves backwards and forwards in a line, towards and away from the Sun in a year", p. 17) may not give a true reflection of the teachers' knowledge. Atwood and Atwood (1996) found that only one primary pre-service teacher (of 49) had a true scientific understanding of the seasons, and the distance theory was the major alternative conception identified. These researchers considered, however, that the participants' conceptions were not firmly held, and could be altered by instruction. Parker and Heywood's (1998) results confirmed the other teacher studies, but their discussion of language issues (such as rotation and revolution) and teachers' PCK (such as the key concept of how light shines on a sphere) make their article a particularly important one in the field. Their error in Figure 3.3 which shows the scientific explanation of the seasons as being "when the northern hemisphere is nearer the sun it is summer …. When … the southern hemisphere is nearer the sun so it is winter in England" (p. 510) demonstrates how careful researchers need to be in their use of diagrams and captions. Kikas' (2004) quantitative study involving secondary teachers found that 80% of the biology and science teachers (n = 58) were able to provide a scientific explanation for the seasons compared with the humanities (15%, n = 51), primary (16%, n = 57), and trainee teachers (37%, n = 32). A constructivist intervention for teachers described by Trumper (2006) resulted in a significant change in knowledge about the seasons for the experimental class.

Earth–Sun–Moon System and Moon Phases

On Earth, we observe Moon phases because as the Moon orbits the Earth over a 28-day period, differing amounts of the Moon's surface reflect light from the Sun. When the Moon is on the opposite side of the Earth from the Sun, we can see one whole side of the Moon lit up: the "Full Moon". When, on the other hand, the Moon lies between the Earth and the Sun we see no Moon for up to three nights: the "New Moon". Between these two extremes, the Moon has completed a proportion of its orbit, and a half or crescent Moon is observed. Because the Moon orbits the Earth at an angle of about 5° with the plane of the Earth's orbit around the Sun, a solar eclipse occurs only rarely, while a lunar eclipse (the Earth's shadow across the Moon) is more common.

We consider research into students' and teachers' understanding of the Earth–Sun–Moon system and the Moon phases together, as the two topics are closely related. Like the day/night cycle, many researchers report on the Moon studies as part of a larger investigation, and only a quarter of the 36 studies examined the Moon alone. The research strongly suggests that explaining the three-way relationship between the Earth, the Sun, and the Moon, and why the Moon phases occur, is very challenging for most people. A quarter of the articles examined teachers' conceptions or conceptual change, while the remainder worked with primary and secondary students. Nearly half of the researchers used models during their data collection.

The earlier studies (Baxter, 1989; Jones et al., 1987) identify five notions of Moon phases or spatial relationships between the Earth, the Sun, and the Moon, and relate these to developmental patterns in their participants. Baxter noted that the commonest alternative conception was that the phases are due to the shadow of the Earth falling on the Moon, which almost all subsequent researchers have also identified (e.g. Schoon, 1992; Trumper, 2001a, 2001b). While most studies have explained this alternative conception as naïve thinking, Engeström (1991) has a very different explanation. He suggests that the loss of the correct size and scale when the Earth–Sun–Moon system is modelled, and the poor diagrams reproduced in textbooks on this topic have resulted in the culturally produced artefact of the Earth's shadow as people's explanation for the phases. Unfortunately, although subsequent authors have also reported on poor diagrams of the Moon phases in books (e.g. Dove, 2002; Dunlop, 2000; Martinez Pena & Gil Quilez, 2001; Trundle, Troland, & Pritchard, 2008), no one has attempted to account for the Earth's shadow explanation in these terms, or test this hypothesis. Dunlop suggests that any model which is not to scale can be confusing, even the traditional orrery which has been used for generations in the demonstration of astronomical relationships. If Engeström and Dunlop are right, curriculum developers, teachers, and textbook writers need to consider seriously how this topic should be taught in future.

Throughout the review period, studies have found that although students are able to *describe* the Moon phases, most of them are unable to explain *why* the phases occur, or give a coherent account of the Earth–Sun–Moon system. As in their work on the day/night cycle, Sharp (1996), Roald and Mikalsen (2000, 2001), and Liu (2005) used Vosniadou's theories to identify and explain students' scientific, synthetic, and intuitive mental models for the Moon phases. However, the authors found that mental model theory was much more difficult to apply, synthetic conceptions were more prevalent, and that students held a "plethora of different … complicated conceptions" (Roald & Mikalsen, 2001, p. 436). A single study looked at students' conceptions of the solar eclipse (Mohapatra, 1991), and found that in India, rituals and folklore associated with the phenomenon generated a number of alternative conceptions.

In view of the topic's difficult conceptual nature, four studies have attempted carefully structured teaching activities to enable students to understand the relationship between the Earth, the Sun and the Moon better. Stahly et al. (1999) worked with 8- and 9-year-olds, Trundle, Atwood, and Christopher (2007a) with 9- and 10-year-olds, Barnett and Morran (2002) with 10- and 11-year-olds, and Taylor et al. (2003) with 12- and 13-year-olds. Stahly and colleagues found some limited changes in students' conceptions, but their study suggests that the topic may be too complex for Grade 3 level and they question whether such students are cognitively developed enough to understand lunar phenomena. Conversely, Trundle et al. (2007a) and Barnett and Morran (2002) found that the carefully scaffolded conceptual change model they presented *did* enable Grade 4 and 5 students to explain the Earth–Sun–Moon system more coherently, and they attributed this to the degree of the students' immersion in the intervention. Taylor and colleagues found that the students' understanding about the Moon was still limited, even after the intervention (Taylor et al., 2003). This might possibly be explained by the intervention covering a range of astronomy concepts, rather than the focused instruction of Barnett and Morran.

Studies of teachers' understanding of the Earth–Moon–Sun system and the Moon phases mirror the research with students: the complexity of the phenomenon is such that they struggle to make coherent explanations, although they are more aware of their contradictions and incoherence than school students. In Mant and Summer's studies, the majority of primary teachers agreed with the proposition that the Moon orbits the Earth, but most of their explanations of the phases invoked "something in the way" of the Moon, such as the Earth's shadow (Mant & Summers, 1993; Summers & Mant, 1995). More positively, studies of conceptual change among teachers have determined that interventions using three-dimensional models were effective in improving their understanding of the topic. Trundle's studies together with her colleagues (Bell & Trundle, 2008; Trundle, Atwood, & Christopher, 2002, 2006, 2007b) found that after instruction, teachers were able to express more scientific views than they had previously, while Parker and Heywood's (1998) paper is very helpful in identifying key features of teachers' PCK on this topic, rather than merely concentrating on the science content. Recent intervention studies with teachers (Mulholland & Ginns, 2008; Ogan-Bekiroglu, 2007; Shen & Confrey, 2007; Suzuki, 2003) suggest that the development of PCK, detailed metacognitive discussion, and mental modelling enables teachers to acquire a clearer understanding of the Earth–Sun–Moon system. However, as with students, some aspects of understanding the Earth–Sun–Moon system remain difficult for teachers.

Solar System

The solar system is regarded as the Sun and nine (now eight) orbiting planets, as well as other celestial objects such as the planets' moons, asteroids, comets, meteoroids, and interplanetary dust. Objects are held in orbit around each other and the Sun due to the force of gravity.

While knowledge of gravity and orbits as well as the concept of scale are key requirements of an understanding of how the solar system works, much school knowledge for this topic seems to be limited to little more than the names and composition of the planets (e.g. Adams & Slater, 2000; Department of Education, 2002). Thirteen studies are examined in this review, two of which are of primary teachers. Treagust and Smith (1989), in their Australian study found that high school students had a very limited understanding of the role of gravity in the mechanism of planetary motion. Since that time, the few studies on this topic have focused on a model of the Sun and its orbiting planets rather than the mechanism. Two questions in Schoon's (1992) multiple-choice questionnaire identified alternative conceptions regarding the planets' visibility at night. Sharp's interviews with 10- and 11-year-olds (Sharp, 1995, 1996) revealed that over 50% (n = 42) held a scientific model of the system, while the remainder showed a variety of alternative conceptions. Candela (2001) described a classroom setting with students in the same age range as Sharp's, in which the teacher directed the discussion to draw out the main concepts of planetary motion. Although her observations may well be valid for the class she observed, her conclusions that "the children … display a sound grasp of basic astronomy" (p. 121) and "they share a scientifically sound concept of planetary movement" (p. 123) are optimistic, and may not be generalisable to other contexts. Substantial improvements in knowledge acquisition about the solar system by 9- to 11-year-olds resulted from an intervention described by Sharp and Kuerbis (2006). This study interrogated knowledge restructuring, and the authors suggest that pathways of mental models shown by participants in the study reveal unusual patterns which they relate to the theory of chaos in cognition. Based on the notion of the unpredictability of learning outcomes, chaos theory suggests that radical knowledge restructuring occurs at times of cognitive conflict.

Two studies (Mant & Summers, 1993; Summers & Mant, 1995) showed that while some primary teachers held a scientific view of planetary motion, others held various alternative conceptions, such as the inclusion of stars within the solar system. The authors speculate that astronomy misconceptions are acquired from informal sources such as television and newspapers. However, we consider that the nature of their 1995 instrument (57 true/false questions) might have resulted in some of the inconsistencies the authors found.

Stars and the Sun

A star is a massive body of gas, mainly hydrogen and helium, which undergoes a process of nuclear fusion in its core, resulting in energy being released. This energy radiates into space. On Earth we experience the radiation of our closest star, the Sun, mainly in the form of heat and light which allow life to exist on our planet.

Although some knowledge of stars would seem to be a basic requisite for any astronomy education at school level, we identified only eight studies (all conducted since 1990) across a wide age range (7–19 years). The only two articles which focused exclusively on this topic reported on quasi-experiments conducted in planetaria.

The earliest study (Finegold & Pundak, 1991) was quantitative, using a multiple-choice test of 15 items with 13- to 18-year-olds in Israel. Although eight of the 15 items were concerned with the Sun and stars, the study was concerned more with testing and conceptual frameworks in astronomy than with astronomical knowledge about stars. Only two questions were analysed in detail in the paper, and the authors found that 69% (n = 169) of students believed light from stars was a reflection of sunlight. However, the idiosyncratic nature of several of the multiple-choice items suggests that the study has limited significance. For example "What is the difference between a planet and a fixed star?" A: there is no difference between them; B: there is a difference. I don't know what it is; C: a planet reflects the light of the Sun and a star makes its own light; D: planets revolve around the Sun. Stars don't move; E: planets revolve around the Sun and stars move in space.

Sharp (1995, 1996; Sharp, Bowker, & Merrick, 1997) included knowledge of the Sun and stars in his study of 10- and 11-year-olds, and found some basic knowledge: three-quarters of the 42 students thought of the Sun as a huge ball of fire and had some idea of its position and movement. Similarly, three-quarters believed stars are round or "star-shaped" (five-pointed), but were not aware of their position in space or their movement. About half the students realised that the Sun is a star. Similar results were found by Roald and Mikalsen (2000), although relatively few participants realised that stars (as opposed to the Sun) are hot matter, and an understanding of a spherical shape was not explicitly expressed. In her analysis of the end-of-year exam for 12-year-olds, Dove (2002) determined that 78% (n = 98) understood that the movements of stars were due to the Earth's rotation, while a study comparing star movements in a planetarium dome demonstration with an equivalent computer display (Baxter & Preece, 2000) determined there was no significant difference between the two interventions for 9- to 10-year-old children. The only other research conducted in a planetarium compared humorous versus non-humorous shows, and determined that there was greater short-term retention of astronomy concepts in the latter (Fisher, 1997).

In a qualitative exploratory study Agan (2004) used Vosniadou's concept of "presuppositions" to analyse the interview responses of 17 students ranging from junior high school to university level. She found a variety of understandings, from descriptive discourse in the younger students to more scientific knowledge in the older group who were completing an astronomy course. She noted that an absence of models limited ways in which students were able to express their ideas, and the study provides a useful basis for future research in this area. Two other recent studies examined the impact of technology-based interventions. Taasoobshirazi and colleagues described how the use of software used in a secondary curriculum resulted in learning gains (Taasoobshirazi, Zuiker, Anderson, & Hickey, 2006). Beare (2007) described how the incorporation of robotic telescopes into coursework led to increased knowledge about stars and cosmology, as well as high levels of enthusiasm for the project.

The Concepts of Size and Distance

In relation to human experience, the massive sizes of heavenly bodies as well as the enormous distances involved in any discussion of space are crucial to the understanding of the other big ideas.

All nine studies which included aspects of "size" and "distance" formed part of other studies, such as those of day and night, the seasons or stars and the Sun, and have been discussed above. Five articles were quantitative surveys, each with up to three questions involving the concepts of size and distance.

In their 1992 study of British primary school teachers' knowledge of astronomical phenomena, Summers and Mant (1995) concluded that few had an accurate knowledge of the scale of the Earth–Sun system, whereas 85% (n = 120) knew that the Moon is smaller than the Earth. Sadler's quantitative study of 1,250 Grade 8–12 students in the USA (Sadler, 1998) had one question on the distance between the Sun and the closest star, which the majority of students were not able to answer accurately. Trumper used Sadler's question and two others concerning the size of the Earth and the Sun in his studies (Trumper, 2001a, 2001b). Trumper concluded that this aspect was one of the weakest areas of high school students' knowledge, with only 20–25% (n = 826) answering these questions correctly. Bakas and Mikropoulos (2003) determined that while 64% of their sample of 11- to 13-year-old Greek students (n = 102) knew the real size of the Earth and the Sun, only 16% of the same students were able to correctly identify the relative distance of the Earth from the Sun. Similar results were found with Turkish students (Cin, 2007) and Agan (2004) has shown that high school students were able to speak of "great distances between stars", but only the undergraduate students could relate the distances to a scale model.

With relatively little evidence, different authors have contrasting opinions on the ability of school-going children to understand the concept of scale in astronomy. Sharp (1996) is relatively optimistic that children of primary school age are capable of grasping "complex and abstract information" about basic astronomy, and that "comparisons involving relative size, distance, age, and time were … useful and familiar to children" (pp. 707 and 709). Conversely, Sadler (1998) suggests that "comprehension of vast astronomical scales appears to remain beyond the reach of students even after taking an Earth science course [or] astronomy course in high school" (p. 283). However, he provided limited evidence in his paper as support, and examination of the test he conducted has proved difficult, as it was never made widely available (Hufnagel, 2002). Bakas and Mikropoulos (2003) considered "that the comprehension of such large distances is meaningless and cannot be easily understood by students of 13–14 years of age" (pp. 956–957). This would appear to be an area ripe for further research, given its crucial role in astronomy and the contrasting claims made by researchers.

Discussion and Implications

This paper has surveyed 103 articles on research into astronomy education over 35 years, identifying a large body of peer-reviewed literature in the area. To answer our first research question (our understanding of learning about astronomy) we categorised the research conducted in terms of big ideas and noted that the majority of the studies examined aspects of the conceptions held by participants. Alternative conception studies dominated science education research from the late 1970s onwards, and by the 1990s scholars were questioning whether further research of this type was profitable (e.g. Georghiades, 2000; Gil-Pérez, 1996). We would disagree with Adams and Slater's review (2000), which recommend the need for "a deeper understanding of student conceptions at the various grade levels" in astronomy in order to "create research-informed learning experiences … to effectively address … student misconceptions" (p. 43). We would contend that the necessary conceptions research has already been done, at least for several of the big ideas taught at school. In addition to more than 30 studies conducted on each of the Earth conceptions, the Earth–Sun–Moon system, and the day/night cycle, there are numerous additional studies we have not cited as they fall outside the selection criteria. There may be scope for conception research to continue in the other big ideas we have identified, but we would contend that these should have the explicit aim of developing teaching–learning sequences (Méhaut, 2004), metacognitive learning (Flavell, 1976; Georghiades, 2000), or PCK in teachers (Loughran et al., 2004). The recent trend towards reporting on intervention studies (16 articles since 2006) which try to change students' conceptions appears to be a more profitable line of enquiry than merely identifying and probing the conceptions alone.

Regarding learning about astronomy, many concepts such as the seasons, the Moon phases, and the concepts of size and distance are counter intuitive and pose great challenges. Evidence from the studies in our review suggests a number of ways of approaching such challenges. Firstly, there is a need for carefully planned teaching activities which use physical models as a key part of the pedagogy. There is considerable support in the literature for modelling activities, both virtual (e.g. Barnett, Keating, Barab, & Hay, 2000) and physical (e.g. Shen & Confrey, 2007) in enabling students to more clearly understand the three-dimensional nature of astronomical concepts. Secondly, complex explanations (as opposed to descriptions) of phenomena involving the Earth–Sun–Moon system (e.g. the Moon phases and the seasons), gravity, and concepts of scale are unlikely to be understood by children before about age 10, and several studies (e.g. Sharp & Grace, 2004; Taylor et al., 2003) discuss at what stages of the curriculum different concepts should be taught. Thirdly, teaching needs to explicitly counter the alternative conceptions acquired through informal sources of information (such as television), and poorly drawn, not-to-scale diagrams. Numerous studies (e.g. Kikas, 2005; Martinez Pena & Gil Quilez, 2001) bemoan the poor quality of many of the resources available for teaching astronomy, and the need for more accurate and less confusing book diagrams and representations. A quick scan of the Internet for teaching ideas about these topics brings up a wide variety of resources, many of limited use, and some just plain wrong. Further, there is a need to develop students' and teachers' visuo-spatial abilities to enhance their ability to understand what both drawings and models represent (Mulholland & Ginns, 2008). Finally, there should be a greater focus on the teaching of distance and size to help explain astronomical phenomena. Although very few studies focused on this big idea, it is crucial to so much of astronomy, from the size of the Earth and the solar system to their relationship to the rest of the galaxy and the Universe. Not only is this concept under-researched, but it is under-taught.

Our review clearly has implications for teacher education, both pre-service and in-service. Several researchers found that primary teachers had similar misconceptions as their students across a range of big ideas (e.g. Atwood & Atwood, 1995, 1996; Summers & Mant, 1995), which suggests the need for improved training at this level particularly their content knowledge and PCK. Some studies noted better knowledge of astronomy concepts among secondary teachers (e.g. Kikas, 2004), while others involving interventions for conceptual change demonstrated improvements in their scientific understanding (e.g. Trundle et al., 2002, 2006, 2007b). It goes without saying that improved in-service training is vital for all teachers if the quality of astronomy education is to be improved.

Our second question involved the methodologies and theoretical frameworks used in the research we reviewed. Quantitative surveys have been reported throughout the review period, but their numbers have remained static over this time. Similarly qualitative studies involving small-scale surveys (mainly case studies) have remained more or less constant since the early 1990s. In contrast, both quantitative and qualitative intervention studies started being reported in the mid-1990s, and have become by far the dominant category of research since that time. This is in line with international trends in science education and the evidence-based policy movement (Young, Ashby, Boaz, & Grayson, 2002). Most of the recent intervention studies (since 2005) have provided full descriptions of their instructional methods. This is strongly encouraged so that teachers (and researchers) can learn from the best practices. The most commonly identified theoretical framework used by researchers was that of "conceptions". The earlier studies (1970s and 1980s) mainly consisted of researchers attempting to identify students' misconceptions, and (to a lesser extent) comparing these across cultures. By the 1990s, the research was becoming more theorised, with interest shifting to Vosniadou's mental model theories, often coupled with how students were able or struggled to change their non-scientific conceptions. Cross-cultural, mental model, and conceptual change theories have dominated research articles since the turn of the century. Sharp's work with younger children (Sharp & Grace, 2004; Sharp & Kuerbis, 2006; Sharp & Sharp, 2007) has opened interesting debates on the curriculum and mental models. Bryce's longitudinal work across the age range has thrown significant light on conceptual change and cultural mediation (Blown & Bryce, 2006; Bryce & Blown, 2006), while Trundle's work has shown similar insights into conceptual change with teachers (Bell & Trundle, 2008; Trundle et al., 2002, 2006, 2007b).

Just less than 40% of the studies used interviews and a similar number used physical models as part of their data collection methods. Several researchers (e.g. Schoultz et al., 2001; Suzuki, 2003) note that participants' manipulation of models during the interview process enabled them to reach a scientifically correct conclusion, which would not be available to subjects writing answers to written tests. In the field of astronomy, we would contend that to try and ascertain participants' understanding of concepts without allowing them to manipulate models is likely to result in an underestimation of their knowledge of the topic being investigated. However, Bryce and Blown (2006) note that in order to investigate young children's notions of (for example) the Earth, concrete models should be avoided, in order that the children's true conceptions can be probed by Piagetian clinical interview procedures refined by Nussbaum and colleagues. With this proviso in mind, we therefore suggest that future researchers promote the manipulation of physical models while subjects are being questioned, either by written or interview methods, so that a more accurate estimation of their knowledge can be obtained. We further suggest that a full description of the models be provided, so that subsequent research can build on the findings established.

Relatively few researchers identified language as being a barrier to understanding concepts in astronomy, but it is likely to be important, especially for second-language learners (Rollnick, 2000). Parker and Heywood (1998) discussed teachers' confusion around the terms "orbit" and "spin", and others such as Dove (2002) and Stahly et al. (1999) referred briefly to similar issues. Even the researchers themselves sometimes used confusing terms when questioning their participants: Parker and Heywood's (1998) error in their Figure 3.3 and Klein's (1982) reference to "earth rotates around sun" (p. 105). Studies involving the language of astronomy would therefore likely be a good avenue for future research.

Our third research question (the future agenda) has been answered in several of the recommendations we have made above. The research topics in our review mirror what is taught in schools and to teachers. Early in this new century, astronomers Pasachoff, Sadler, and others presented their views about the most appropriate introductory astronomy to be taught at tertiary level. Although there was some consensus that topics such as the seasons and Moon phases were appropriate for school level, there was little agreement regarding the teaching of the "new" astronomy (cosmology and astrophysics) to non-science undergraduate students (Pasachoff, 2001, 2002; Sadler, 2001, 2002). At the school level there has been little discussion on what are the most appropriate topics to cover, though Sharp (1999, 2004) has suggested reasons for including the Earth in space at the lower end of schooling and provided a view on the place of astronomy within a primary science curriculum. We suggest that research into the most relevant big ideas in astronomy in relation to countries' curricula would benefit their schooling systems.

What emerges from our review is that conceptually difficult topics such as seasons and the Moon phases have been well-researched, but few of the findings are reaching teachers in schools. Part of the problem may be due to the subject of astronomy falling across the disciplines of physics, geography, astronomy, and earth science, resulting in under-educated teachers teaching it to students. It is vital that each disciplinary constituency becomes familiar with the teaching methods and research carried out in the others. There has been a tendency for research into astronomy education to be reported in separate disciplinary "silos", and for the field to flourish there needs to be a greater emphasis on inter-disciplinary cooperation. Similarly, astronomy education researchers need to find innovative ways in which to disseminate their findings to teachers (Cordingley, Bell, & Evans, 2007). The online journal *Astronomy Education Review* is a good example, and needs to be complemented by the astronomy education community becoming more involved in teacher professional development and investigating teachers' needs. Empirical investigations in astronomy education over the past 15 years have made enormous strides; promoting effective learning in the classroom, lecture room, and laboratory will ensure that the research has been a valuable endeavour.

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