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INDEX

The Planck Visualization Project:
Immersive and Interactive Software for Astronomy and Cosmology Education

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We describe two simulations for teaching astronomy and cosmology which we have developed as part of the education and public outreach program of the international Planck Mission. The first is an interactive, Virtual Reality simulation of the Planck Mission, which supports learning of basic concepts in Solar System astronomy. The second is an interactive visualization and sonification of the Cosmic Microwave Background, the oldest radiation of the universe, which supports learning of basic concepts in contemporary cosmology. The simulations, as well as our accompanying curricula and publications, are available on our website: http://planck.caltech.edu.
Keywords: *Virtual Reality for Science Education, Dynamic and Interactive Science Learning Environments, Explorative Learning; Visual Learning*

Planck Görselleştirme Projesi:
Astronomi ve Kozmoloji Eğitimi İçin Üç Boyutlu ve Etkileşimli Yazılım

Bu çalışmada, The International Planck Mission Programı kapsamındaki eğitim ve sosyal yardım programının bir parçası olarak astronomi ve kozmoloji öğretimine yönelik geliştirdiğimiz iki simülasyonu tanıtmaktayız. Bunlardan birincisi, Güneş Sistemi astronomisi temel kavramlarının öğrenilmesini destekleyen Planck Mission etkileşimli Sanal Gerçeklik simülasyonu. İkincisi ise, çağdaş kozmolojinin temel kavramlarının öğrenilmesini destekleyen, Evrenin en eski ışıması Kozmik Mikrodalga Arkaplanının etkileşimli canlandırılması ve seslendirmesi. Bu simülasyonlar, bunlara ait eğitim programları ve yayınlar, web sitemizde mevcuttur: http://planck.caltech.edu.
Anahtar Kelimeler: *Fen Eğitimi için Sanal Gerçeklik; Dinamik ve İnteraktif Fen Öğrenme Ortamları, Açınsayarak Öğrenme, Görsel Öğrenme.*

Introduction:

It is estimated that each year more than 250,000 undergraduates take introductory astronomy in the United States and Canada (Partridge & Greenstein, 2004), yet in spite of the popularity of college astronomy courses, surveys suggest that a large segment of the American public has a rather limited understanding of the Earth's place in space (Fraknoi, 1998; 2004). Numerous studies suggest that many college students hold misconceptions about the Solar

System and the Earth's place within the cosmos (Shapiro, Whitney, Sadler, & Schneps, 1987; Barnett, Keating, Barab, & Hay, 2000; Bakas & Mikropoulos, 2003), including the notion that the Sun goes around the Earth (Yair, Mintz, & Litvak, 2001), and other "folk concepts" (Zeilik, Schau, & Mattern, 1998). Such naïve viewpoints may not be corrected by traditional lecture-based instruction, in which students are passive recipients of knowledge (Wallace, Prather, & Duncan, 2012). Cosmology is one of the most popular topics in introductory college astronomy, yet also one of the most difficult to convey (Wallace, Prather, & Duncan, 2011). Concepts such as the Big Bang, expansion and evolution of the universe, evidence for dark matter, and the idea that the actual universe extends more than three times farther than the observable universe are problematic for students to grasp (Wallace et al., 2012; Davis & Lineweaver, 2004).

In this paper we discuss previous studies that have demonstrated how the use of virtual environments and game-like simulations have improved students' conceptual reasoning in introductory astronomy. We then discuss two new simulations that we have developed for undergraduate astronomy and cosmology, and suggest teaching strategies for incorporating our simulations into the teaching and learning of introductory astronomy and cosmology.

Interactive Simulations and Virtual Immersive Environments in Astronomy Education

The U.S. National Research Council recommends computer simulations in science education because they

> … enable learners to see and interact with representations of natural phenomena that would otherwise be impossible to observe—a process that helps them to formulate scientifically correct explanations for these phenomena.
>
> (National Research Council Report, 2011)

Indeed, within the last decade a number of studies using interactive simulations and virtual immersive environments in introductory astronomy report improvement in students' understanding of basic concepts over traditional lecture-based methods (Yu, Sahami, & Denn, 2010; Gazit, Yair, & Chen, 2005; Bakas & Mikropoulos, 2003; Yair, Mintz, & Litvak, 2001; Barnett, Keating, Barab, & Hay, 2000). Savage, McGrath, McIntyre, & Wegener (2010) obtained substantial gains in first-year physics students' conceptual understanding of Special Relativity when they combined virtual reality simulations with traditional instructional methods. These authors emphasize that it is the immersive, interactive, first-person, and game-like nature of such simulations that has the potential to facilitate students' discovery learning. Barab and Dede (2007) cite several studies which illustrate how game-like virtual learning experiences provide a strong sense of engagement with science content for all learners. Other studies suggest that a combination of learning in virtual environments and real world experiences may provide the optimal pedagogical strategy in science education (Winn et al., 2006).

We present two new simulations for astronomy and cosmology education. Originally developed as outreach tools in support of the international Planck Mission, these simulations directly support learning goals for introductory college astronomy (as suggested by Partridge & Greenstein, 2004, e.g.) and basic cosmology (as suggested by Wallace, et al., 2012, e.g.). Our Planck Mission in Virtual Reality (PMVR) simulation runs in a virtual solar system, and offers a non-competitive game-like, immersive experience in which the user can interact with the satellite as it leaves the Earth, arrives at its orbital location around the second Lagrange Point (L2), and scans the sky. The user can explore the solar system, navigate or use hot keys to jump from planet to planet, while the satellite 'paints' the image of the Cosmic Microwave Background on the sky. Time in the simulation begins on May 14th, 2009 with the launch of Planck from French Guiana. Even after the mission ends, the user can fast-forward time to observe alignments of the planets into the future.

Our Visualization and Sonification of the Cosmic Microwave Background (CMB), or Sounds of the CMB, utilizes the technique of sonification to explore hypothetical universes derived from different cosmological models in sound space. This simulation supports learning objectives in cosmology, the origin of the universe, and the origin and meaning of the CMB. In addition, it can appeal to art and music students because it utilizes the physics of music to teach about the physics of the early universe. In the next section we present a brief overview of the CMB and the Planck Mission, followed by a brief discussion of each simulation. The technical details and theoretical background of our simulations are described in Moreland, Dekker, & van der Veen. (2011), McGee, van der Veen, Wright, Kuchera-Morin, Alper, & Lubin (2011), and van der Veen (2010).

About the Cosmic Microwave Background and the Planck Mission

Formation of the CMB. According to our current understanding, the universe began some 13.7 billion years ago in an unimaginably hot, dense, compact state, from which it suddenly expanded after an unknown period of dormancy. As the universe expanded and cooled, it became a fluid of tightly coupled matter and radiation. Dark matter, which does not interact electromagnetically, condensed first, driving oscillations which then propagated through the expanding universe as extremely long wavelength sound waves in the matter-radiation fluid. At approximately 380,000 years after the so-called Big Bang, the universe became cool enough for matter and radiation to decouple, and light could travel freely for the first time. The pattern of those primordial sound waves was imprinted in the light that last scattered off their surface as red and blue shifts, seen today as microKelvin fluctuations in the CMB (Fig. 1a). The power spectrum of the CMB (Fig. 1b) encodes the physical parameters of the universe such as the relative proportions of normal matter, dark matter and dark energy, ionization history, expansion rate and possible primordial anisotropy. Thus it has been a major goal of experimental cosmology over the past two decades to derive the power spectrum of the CMB fluctuations from increasingly high-precision maps (Efstathiou, et al., 2005).

About the Planck Mission. Planck is an international mission, led by the European Space Agency with significant contribution by NASA, designed to improve our understanding of the origin and evolution of the universe. Launched on May 14, 2009, Planck has been mapping the microwave sky in nine frequency channels (30 to 857 GHz), with a temperature sensitivity of a few microKelvin, and spatial resolution as fine as 5 arc minutes. The main scientific objective of Planck is to measure the spatial anisotropy of the CMB with an accuracy set by fundamental astrophysical limits. Planck will extract essentially all the information contained in the CMB and its power spectrum, with which to constrain models of how the universe originated and evolved (Efstathiou et al., 2005 and http://sci.esa.int/science-e/www/area/index.cfm?fareaid=17). Planck is considered a decadal or legacy mission, and is the third satellite (after CoBE and WMAP) to map the entire sky in microwave frequencies.

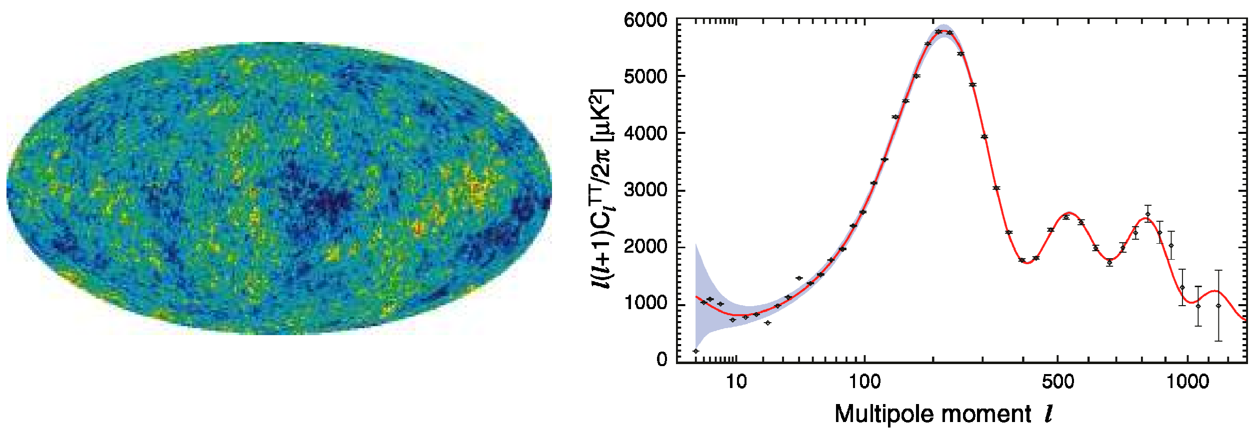

Figure 1. 1a (left): Map of the microKelvin fluctuations in the Cosmic Microwave Background (CMB), WMAP Satellite. 1b (right): Power spectrum of the CMB, WMAP Satellite, 7-year data release.

The Planck Mission in Virtual Reality

The Planck Mission in Virtual Reality (PMVR) is designed for use in a variety of environments, from a multi-user virtual immersive space in which the instructor ‘drives,’ and the students wear special glasses which create the 3D effect, to a single-user virtual world available on a PC, in 2D or 3D modes, in which the individual user is the driver. The PMVR embodies the three key features of a successful VR environment of autonomy, presence, and interaction described by Zeltzer (1992).

There are two scenes from which to choose: *Planck in Space*, and *Planck Instruments* (Fig. 2). Planck in Space is especially useful for teaching basic Solar System astronomy, in addition to illustrating the trajectory and orbit of the Planck satellite. In the current version of the software, the user can change the background from a composite image of the Milky Way to a view of the constellations. With the orbits toggled on, the background includes the Celestial Equator and the Ecliptic. The Earth’s orbit is colored red, so as to provide a constant reference point. Students can see how the planets’ orbits lie on the Ecliptic, while the Moon’s orbit is tilted relative to the Ecliptic (useful for explaining why a lunar eclipse does not occur every month), and how the Celestial Equator, Ecliptic, and plane of the galaxy are inclined relative to each other. With a little practice, students can learn to fly through the Solar System and search for each planet by following the path of its orbit. The small sizes of objects in the Solar System relative to their distances very quickly become apparent!

The Instruments scene allows the user to virtually fly inside the satellite and explore it. There are twelve hot zones where information about the satellite appears, presenting a game-like

Figure 2. Left: Initial screen, Planck in Space. Right: Planck Instruments screen.

challenge to the student to find them all. ‘Flying’ on a PC is accomplished by a combination of arrow keys and mouse strokes, while in a 3D theater the simulation works with a 6-df wand. A user can explore the inside of the satellite, such as flying into one of the feed horns which collect microwaves of a particular frequency, and flying along the waveguides, approximating the path a photon would take down to the detectors (Fig. 3). Before running the simulation, the instructor can edit the configuration file so as to select the features s/he wishes to be available to the students.

Figure 3. 3a (left): Close-up of Planck's instrument panel. 3b (right): 'Flying' inside one of th 44-GHz feedhorns.

Sounds of the CMB: Visualization and Sonification of the Cosmic Microwave Background

Our Sounds of the CMB is designed to help students develop an understanding of the main science goal of the Planck Mission: to extract essentially all the information contained in the CMB temperature anisotropies, with which to constrain models of the universe (Efstatiou, et al. 2005). The simulation consists of two parts: visualization and sonification, which can be run together or separately. The visualization consists of the map of simulated temperature anomalies of the CMB and their angular power spectrum, which have been computed using the public domain Code for Anisotropies in the Microwave Background (CAMB) - the same modeling software used by the international cosmology community (Lewis, Challinor, & Lasenby, 2000). The current reference model is based on the WMAP 2009 published values; however, as soon as the new Planck CMB data are released, we will replace the WMAP reference model with the new Planck values.

The graphic interface has two sliders which allow the user to choose between model universes with different proportions of normal (baryonic) matter, dark matter, and dark energy (Fig. 4). Both the map and the power spectrum change in response to the changing model parameters, as does the sound. A third slider allows the user to adjust the color-temperature mapping scheme, shown on the temperature bar at the top of the screen (Fig. 4). Other features of the visualization include zooming in and out, rotating the sphere in any direction, or rotating the user's viewpoint horizontally or vertically.

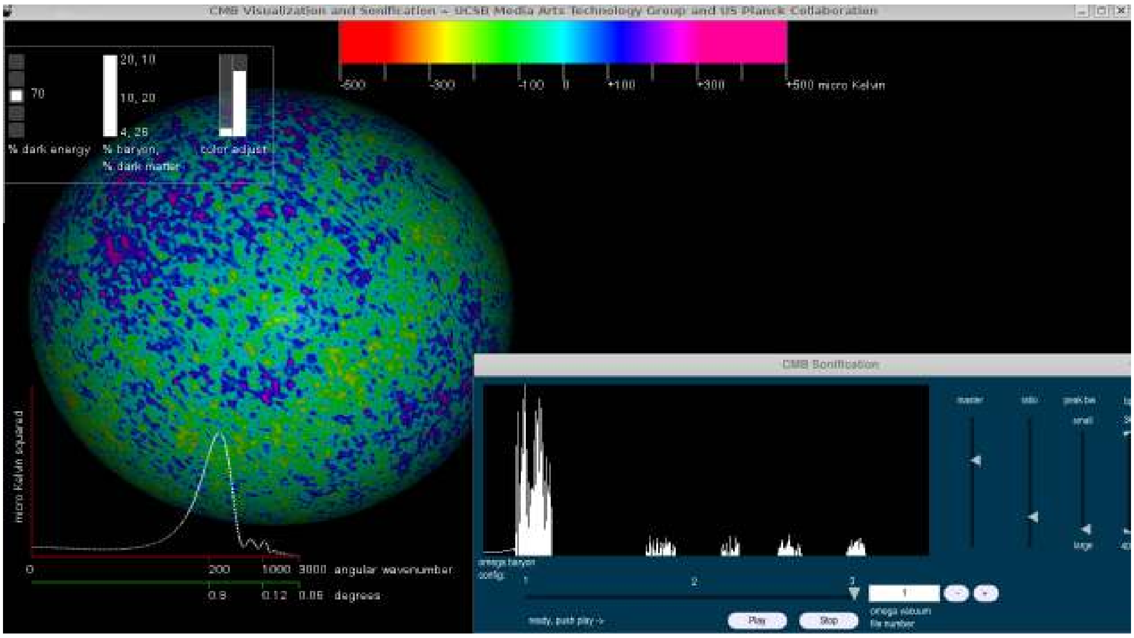

Figure 4. Visualization and sonification of the CMB. Shown here is an unphysical model with the correct proportion of dark matter (70%), but 5 times too much baryonic matter and less than half as much dark matter as has been assumed from previous CMB measurements.

Each model universe produces a different sound, with different harmonic content (Fig. 4, lower right insert). The user can vary the peak width to change the timbre of the sound, as well as total band width to listen to individual harmonics, thus effectively exploring the features of the CMB power spectrum in sound space. It is interesting to note that small changes in the density parameters of the universe produce clearly audible changes in the sound, while the corresponding features in the visual map are much less apparent.

Pedagogical applications of the Planck Mission Simulation in Virtual Reality

The PMVR supports learning objectives for introductory astronomy (Partridge & Greenstein, 2003, e.g.). Because of its 'back story' of an actual satellite which is orbiting the second Lagrange point in the Earth-Sun system, the PMVR provides a real-world example with which to discuss launching space probes, gravitational fields, and why different orbits are chosen for different missions. The immersive nature of the simulation provides an opportunity to help students develop their cognitive spatial reasoning, while the dynamic nature of the simulation gives a 'gut-level' understanding that the Earth and all the planets are in constant relative motion.

Kepler's Laws. It is fairly straight forward to demonstrate shapes of planetary orbits using the PMVR by navigating above the plane of the orbits and then turning around and looking down, as shown in Figure 5, for example. A popular misconception among students is that, because Kepler's Laws state that the planets orbit the Sun in elliptical orbits, the orbits are highly elliptical, as often portrayed in text books. It is quite apparent in the simulation that the orbits are only slightly elliptical, with Mercury's orbit having the greatest ellipticity.

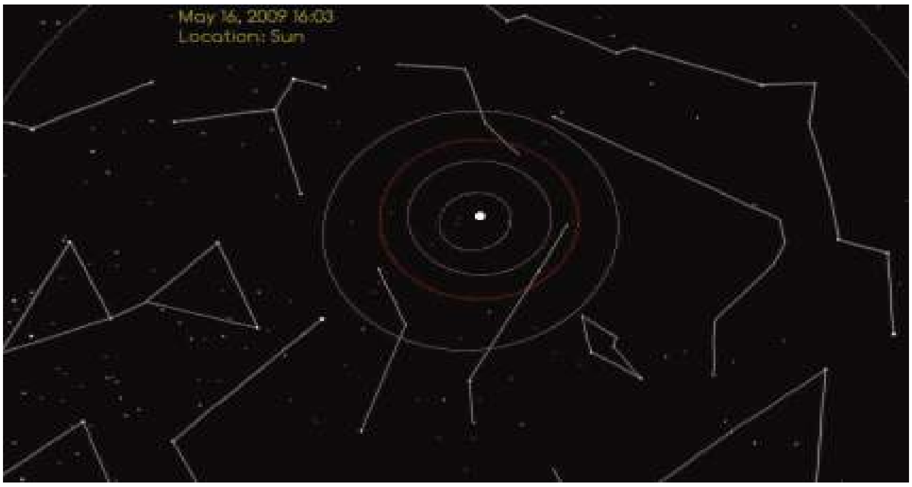

Figure 5. View from 'above' showing the orbits of Mercury, Venus, Earth (colored red), and Mars; Jupiter's orbit is barely visible, cutting across the upper corners in the image.

Supporting observations. It is also possible to demonstrate the reasons for certain terrestrial observations by being in the immersive environment of the virtual Solar System and observing from different perspectives which are not possible on Earth. For example: The question of why the Moon always keeps the same face towards the Earth can be answered in the virtual environment by following the Moon around its orbit from a perspective fixed on the Earth (Fig. 6), and then 'flying' above the plane of the Moon's orbit and following it on its path around the Earth from an external perspective (Fig. 7).

An instructor can use the immersive environment to explain why we see the various planets in different directions, looking toward or away from the Sun. For example, this winter (2012) there has been a spectacular view of the planets Venus and Jupiter in the Northern Hemisphere as they approached each other and then appeared to trade places. By fast-forwarding the simulation to the desired date, the instructor can demonstrate how it is possible to see Venus, an inferior planet, and Jupiter, a superior planet, in the same direction of the sky (looking toward the Sun just after sunset), and illustrate why these two planets appeared to change places from our perspective. An example of this alignment is shown in Figure 8 for the evening of March 2, 2012, for the actual sky (8a) and the simulation, (8b).

Figure 6. View of the Moon, from inside its orbit. The Earth is ‘behind’ the camera. From this perspective the user can follow the Moon as it orbits the Earth, always keeping the same face to the ‘camera.’

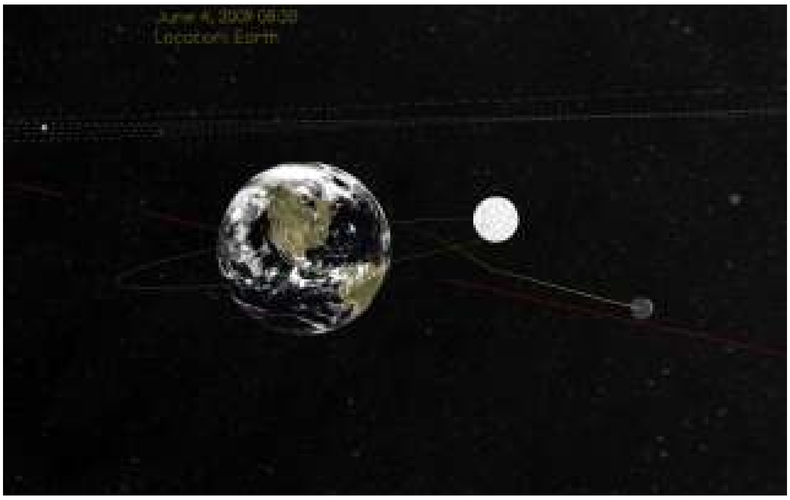

Figure 7. View from outside the Moon’s orbit. Object scale is 25x. Mars is visible in the background on the left, and Planck is seen heading for L2, beyond the Moon to the right.

An ideal implementation of the PMVR would be for an instructor to first take the class as a whole on a guided virtual tour of the solar system and investigation of the Planck satellite in an immersive 3D environment, and then assign students to work through independent explorations in either 3D or 2D mode on a PC. Many campuses now have virtual immersive spaces or 3D theater capability, but even without such technology, a 3D experience can be achieved inexpensively by projecting the simulation onto a screen using the anaglyph mode, and giving students red-cyan glasses, which can be purchased in bulk for around 10 cents each.

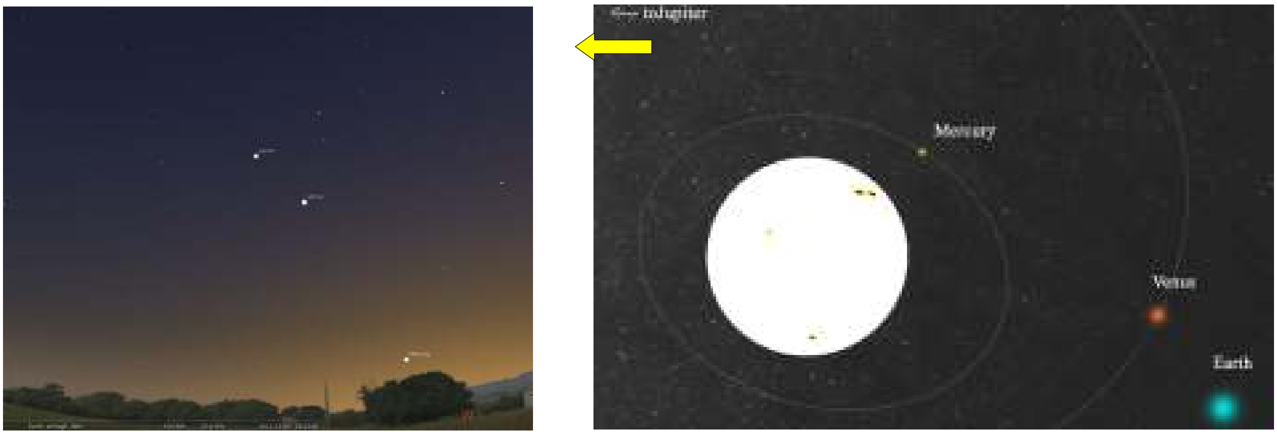

Figure 8. 8a, Left: View from Ireland of Mercury, Venus, and Jupiter in the evening sky, March 2, 2012. (Image credit: Mary Bulman, Armagh Planetarium. Used with permission from http://www.armaghplanet.com/blog/wonders-of-the-march-night-sky.htm, retrieved 22-04-2012.

8b, Right: View from above the ecliptic within the PMVR for the same date, showing alignments of Earth, Venus, and Mercury. Object scale set to 40x; planets were enhanced with Photoshop for the purposes of this image, but actually appear much smaller in the simulation. Jupiter is off the screen, in the direction of the arrow, but would be visible if projected in an immersive VR environment.

In addition to a virtual Solar System, the PMVR contains the actual trajectory of the Planck Satellite, from its launch site in French Guiana to its insertion into a Lissajous orbit around the second Lagrange point (L2) in the Earth-Sun system, and two years of orbital data. One can clearly observe Planck executing its orbit, approximately perpendicular to the ecliptic, especially if one speeds up time in the simulation. Figure 9 is a snapshot taken in the simulation on August 9, 2009, when Planck had just reached its orbit around L2. The idea that a satellite can orbit about an empty location in space is not intuitive, as most students imagine satellites to orbit the Earth or other body in the Solar System, yet Lagrangian orbits have been used for more than a decade (WMAP was placed in an L2 orbit in 2000; the Herschel Infrared Telescope was launched into an L2 orbit with Planck, and the James Webb Space Telescope is planned for launch in 2014 also in an L2 orbit.) Thus, this feature is useful for explaining something about the actual data collection process that lies behind the published maps and images.

Assessment. The PMVR also has the capability of recording movies. With a little practice, students can record their own explorations and demonstrations, including their own narrations. Instructors can use this feature to design both formative and summative assessments of students' understanding. Partridge and Greenstein (2003) report that there is a "a crying need [in astronomy education] for tests and other assessment methods that get at deep understanding, not quickly learned and quickly forgotten facts" (p. 12). Having students record movies using the PMVR offers an alternative form of assessment that instructors can use to probe students' deep understanding.

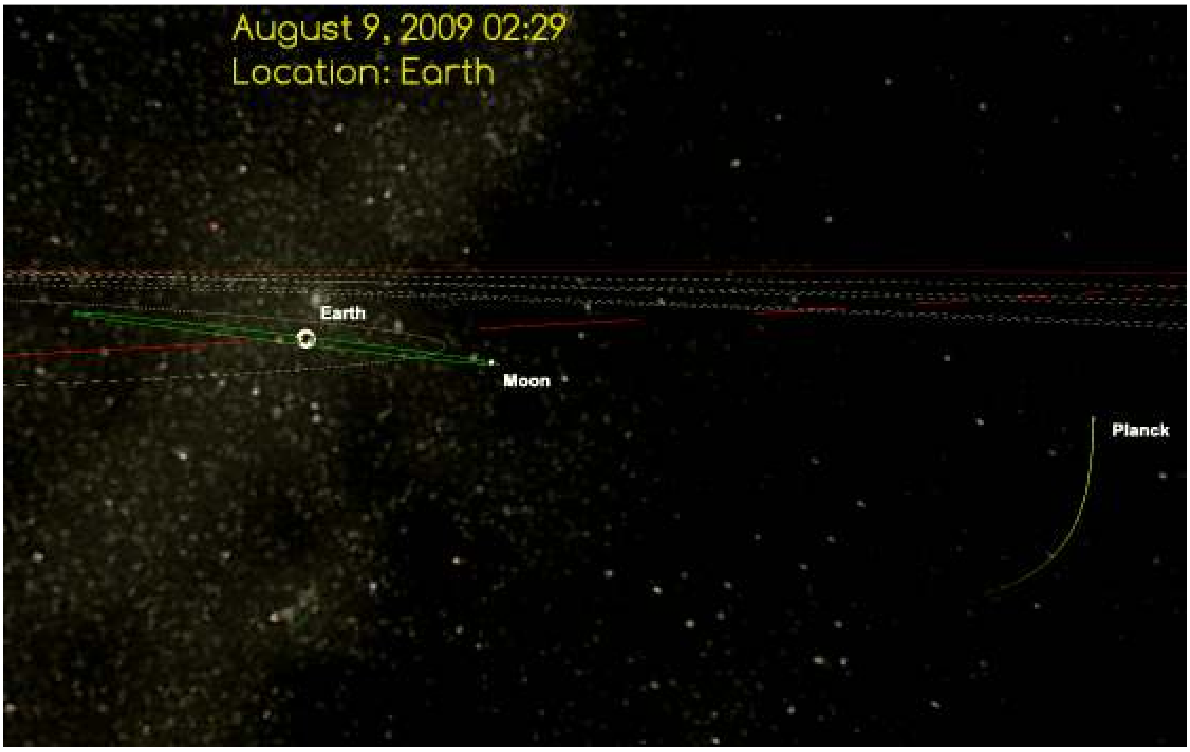

Figure 9. Planck entering its Lissajous orbit around L2. Earth-Moon distance is approximately 350,000 km; Earth-L2 distance is approximately 1.5 million km; radius of Planck's orbit around L2 is approximately 400,000 km, approximately perpendicular to the ecliptic.

We suggest that the Planck Mission Simulation, when combined with night-time observations, provides a powerful means of giving students a real sense of our place in space by connecting observations in the virtual world with observations in the real world. We will begin testing the simulation with introductory astronomy students in the Center for Innovation through Visualization and Simulation (CIVS) at Purdue University Calumet (http://webs.purduecal.edu/civs/) and with test subjects in the Research Center for Virtual Environments and Behavior (RecVeb) at the University of California Santa Barbara (http://www.recveb.ucsb.edu/) during 2012-2013. Results will be reported in a forthcoming paper.

Pedagogical applications of the Sounds of the CMB

Cosmology is a popular topic in introductory astronomy courses, yet also one of the most challenging. Students enrolled in introductory astronomy arrive with pre-existing naive ideas about the nature of the Big Bang and expansion of the universe which are not easily corrected, unless instructors take into account students' prior knowledge (Wallace, Prather, & Duncan, 2012, p.1). Our Sounds of the CMB simulation and accompanying curricula build upon students' presumed familiarity with sound and pitch to guide them to an intuitive understanding of how we derive the physical properties of the universe from the spatial variations in the oldest light we can observe.

The notion of the "sounds of the universe" has a great deal of popular appeal from both the artistic and 'mystical' perspectives, yet it is also a valid scientific model. For the first 380,000 years of its life, the universe was comprised of a tightly-coupled plasma of charged particles and photons through which acoustic waves were propagating. Soon after the 3^0 background radiation was discovered by Arno Penzias and Robert Wilson in 1965, the anisotropy due to primordial acoustic waves was predicted. The fact that this predicted anisotropy has been measured with increasing precision by the CoBE, WMAP, and now Planck missions, as well as a host of balloon-born observations, is one of the most important and successful unions of theory and experiment in contemporary physics, for which two Nobel Prizes have been awarded.[1]

[1] In 1978 Arno Penzias and Robert Wilson received the Nobel Prize for their discovery of the CMB, and in 2006 George Smoot and John Mather received the Nobel Prize for their discovery of the anisotropy of the CMB using the Cosmic Background Explorer (CoBE) satellite.

The Education and Public Outreach group of the Planck Mission in the US has developed a series of curricular materials that support the teaching of cosmology for introductory astronomy, and provide the necessary background for understanding the Sounds of the CMB simulation. Preliminary results of simply giving the simulation to an instructor to use with an introductory class have indicated that without offering the Sounds of the CMB simulation within a correct pedagogical framework, there is the potential for instructors who do not understand it to lead students to an incorrect mental model. We therefore offer the simulation along with cosmology curricula and modeling exercises written by US Planck team members on our website (http://planck.caltech.edu/epo), and are planning a series of workshops for college instructors for the summer of 2013.

The simulation itself can be used in as a demonstration tool by the instructor, or as an exploration for students to compare the sounds of the universe as we currently understand it with hypothetical universes with different ratios of baryons, dark matter, and dark energy. One feature that is dramatically apparent through the sonification is that, for any fraction of dark energy that is selected, increasing the ratio of baryons to dark matter dramatically increases both the pitch and the volume of the fundamental. This is due to the tighter coupling of matter to radiation when the baryon fraction is increased. Why this should be so provides an interesting exploration, and opportunity to model sound propagation with fluids of different densities and mass-spring systems. We provide a database of 45 model universes (15 each of flat, open, and closed models), in which we vary the proportions of baryons, dark matter, and dark energy.

In addition to using the models we provide, students can create their own model universes using interactive software available from NASA, at the CAMB web interface, lambda.gsfc.nasa.gov/toolbox/tb_camb_form.cfm. For more advanced students we would encourage instructors to have students create their own model universes in which they vary some of the other cosmological parameters (such as the Hubble Constant, helium fraction, and reionization time) and compare the sounds of such models with the current best estimates.

Our sonification software can be used independently of the CMB visualization, and thus presents an intriguing means of finding harmonic content in any time series or ordered data set. For example: if a class is observing variable stars, after deriving their light curves photometrically, students could input their light curves as a two-column data array (amplitude as a function of time) into the sonification software and compare the ‘sounds’ of different types of variable stars. Sonification thus applied to variable astronomical phenomena provides a powerful means of allowing blind students to 'visualize' concepts in astronomy that rely heavily on visual data.

Preliminary results with a pilot group of Astro 1 students at an American university suggest that with some refinement of the software, additional curriculum development, and training for instructors, the Sounds of the CMB will be useful in teaching about the importance of the Cosmic Microwave Background in our understanding of the origin and composition of the universe. In the words of one professor who has tested it with two classes of Astro 1 students:

> We teach lots of artists/musicians who totally understand harmonics, and the sonification/visualization speaks to them. We are finding that students are tuning out lectures and the earlier we get them working on the information and visualizing the concepts, the better (Professor A.L., personal communication, 31.01.2012).

Plans for continued development and future research: The software currently runs under Mac-OS 10.0 or higher (Snow Leopard and later versions), and runs clumsily on Linux/ubuntu-64. Our goal for the coming year is to convert the code to HTML-5 for maximum distribution via our website. In summer of 2013 we plan to hold workshops for educators as part of the Cosmos in the Classroom symposium of the Astronomical Society of the Pacific.

In Conclusion:

In 2013 the Planck Mission will release detailed maps of the CMB in nine frequency bands, from microwave to near-infrared, as well as polarization maps of the CMB, and the best-constrained power spectrum to date. When the new data become available, we will incorporate them into both our simulations. Our simulations, publications, and curricula are continually updated, and are available via the Planck main U.S. website, http://planck.caltech.edu/epo. Future results of testing our simulations with students and instructors will be presented in forthcoming publications.

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