Rob Simcoe

Cosmic Dawn
## Hunting for the First Stars in the Universe

A famous New Englander (and avid amateur astronomer) once wrote:

> …*it wouldn't reward the watcher to stay awake*
> *In hopes of seeing the calm of heaven break*
> *On his particular time and personal sight.*
> *That calm seems certainly safe to last tonight.*
>
> — Robert Frost, *On Looking up by Chance*
> *at the Constellations*

The stars have been celebrated throughout art and literature for their constancy, and rightly so, for not much happens to a star during the ~ 100 years that we are around to witness it. Yet over 13.7 billion years of cosmic history, many generations of stars have come and gone — being born in astonishing variety, and sometimes exploding in spectacular, violent deaths. Since the universe has a finite age, at some point in the past there must have been a
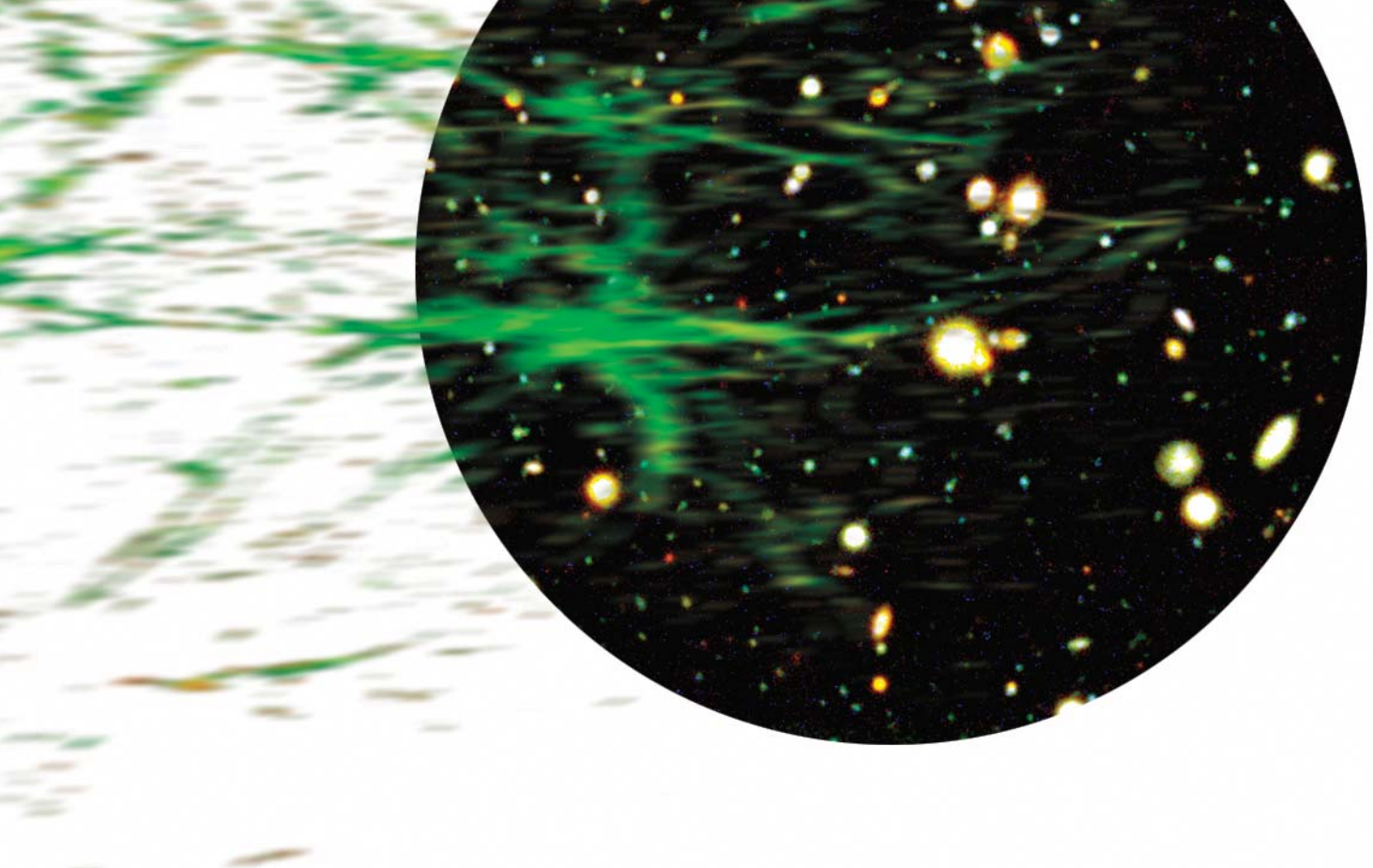
"first star." So, one might ask: how long after the Big Bang did stars first begin to shine? What kinds of environments were conducive to their early formation? And what physical processes governed their assembly? These problems define an exciting research frontier in theoretical and observational astrophysics. Using telescopes with unprecedented clarity and light-gathering power, we can now peer deep into the past, hunting for the fingerprints left behind by stellar relics from the early universe.

The Cosmic Web and Star Formation

Before exploring these techniques, let us examine how stars form and evolve, to provide some physical context. Shortly after the Big Bang, the universe was suffused with an extremely uniform fog of gas, whose density field was smooth to within about one part in 100,000. The density was not precisely uniform, because quantum fluctuations were woven into its fabric during the first 10^{-34} seconds — when the universe was still microscopic in size and hence governed globally by Heisenberg uncertainty relations (a concept pioneered by Prof. Alan Guth at MIT).

Over the next few billion years, gravity amplified these initially tiny density perturbations, enhancing the contrast between low- and high-density regions of the universe. The denser neighborhoods produced stronger gravitational fields, which in turn attracted gas from the sparse regions and collected it into growing haloes
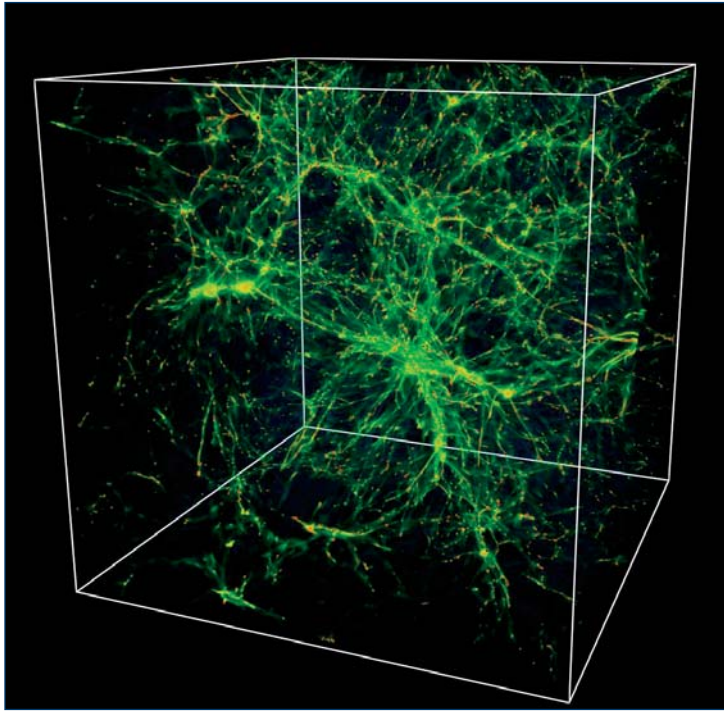
of matter. This created a runaway situation, where the masses and gravitational fields of the dense haloes grew rapidly, pulling in more and more material from the voids. This process gave rise to the cosmic topography we see today, where vast stretches of nearly empty space are peppered with massive stars and galaxies that have collected much of the matter. The particle density contrast between intergalactic space and stellar interiors now exceeds a factor of 10^{32}!

Using modern supercomputers, several investigators (including MIT's Prof. Edmund Bertschinger) have simulated this process of cosmic structure assembly. *Figure 1* shows one such simulation, where the box represents a random cosmic volume roughly 30 million light-years on a side. When programmed with the correct recipe of gravitational and gas physics, dark matter, and cosmological parameters, all of the simulations evolve into networks of crisscrossing, filamentary intergalactic gas structures that penetrate large, empty voids. This matrix has been nicknamed the "Cosmic Web" for its gossamer appearance. At nodes where the web's strands intersect, infalling gas is channeled toward high-density regions where stars and galaxies form in large groups.

This last step — when gas leaves the web and coalesces into galaxies — is quite physically complex, and is the main source of uncertainty in predicting the formation epoch of the first stars. The problem arises when intergalactic gas clouds collapse to galactic sizes and densities; one must devise a way to dissipate the resulting heat of compression. Otherwise, restorative gas pressure will halt gravitational collapse well before the gas can reach the temperatures and densities required to sustain nuclear fusion. No stars could ever be born in this scenario. Fortunately, there are ways around the problem via molecular and atomic radiation, but significant challenges still remain for even the most sophisticated models of early star and galaxy assembly. Various calculations find that the first stars appeared when the universe was between one and ten percent of its present age, a range of uncertainty spanning some 800 million years.

Intergalactic Pollution and the Stellar Life Cycle

There is a path to test and refine these models of early star formation, because the first stars conveniently left behind an irrefutable record of their existence. In the time between the Big Bang and the first starlight, the universe contained only the four lightest elements: hydrogen, helium, lithium, and beryllium. Over time, all the rest of the elements were created in stars. By mapping the chemical concentration

of these secondary elements backwards in time, we can infer the existence of generations of stars that have long since disappeared, in much the same way that an archeologist peels back geological strata to map the fossil record of extinct species.

What astronomers call the "pollution" of the universe was a two-step process, in which new chemicals were first created, and then distributed over wide volumes. It is widely known that stars behave like natural nuclear fusion reactors at their cores, and this is indeed how a star spends the majority of its life. The high temperatures and densities required to sustain fusion are powered by the star's own self-gravity, which literally squeezes energy out of the core. During this phase of a star's lifetime, successively heavier elements on the periodic table are manufactured as the star burns through its available fuel reservoir. The process continues until the stellar core is predominantly composed of iron — the element with maximum binding energy in its nucleus. This means that the star cannot generate energy by fusing iron into heavier elements in its core; it has run out of gas.

When this happens, the star undergoes a rapid transformation. No longer supported against gravity by its internal energy source, it collapses under its own weight. Infalling material bounces off of the hard core and sends a shock wave outwards, triggering a violent explosion that blows away the remnants of the star; in other words, a SUPERNOVA. During the moment of the bounce, the stellar interior is compressed to nuclear densities. This triggers a brief episode of explosive nucleosynthesis that manufactures several additional heavy elements. Also, the atomic nuclei are subjected to a brief, intense bombardment of free neutrons. Through rapid neutron capture and successive beta decay, the atoms in the explosion percolate down the periodic table. In this way, through its long life and brief death, a star converts hydrogen and helium into every other naturally occurring element, up to uranium *(Figure 2)*. Moreover, the supernova debris is scattered back out into the cosmic web, polluting the chemically pristine primordial mixture with freshly minted heavy elements.
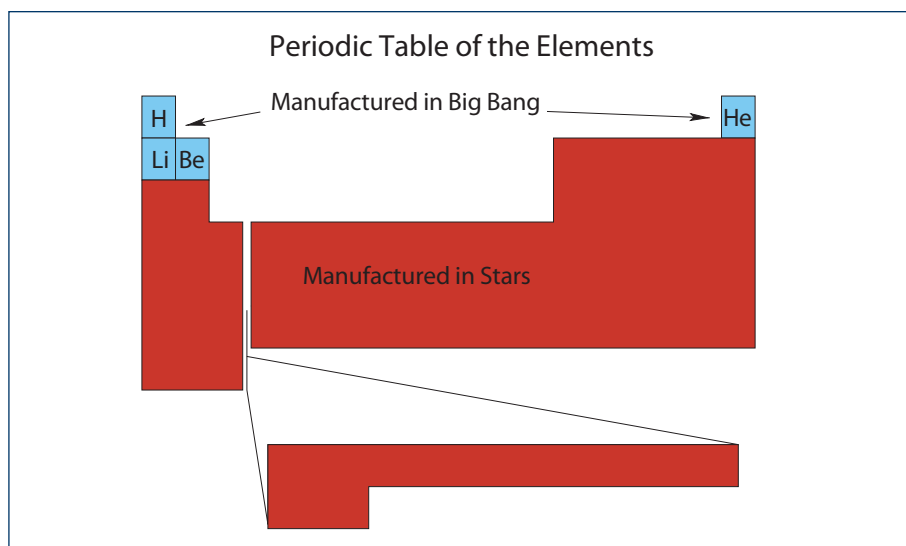

Periodic Table of the Elements

Assaying the Cosmic Web

It is challenging to chart the history of the first stars observationally, because these early populations have not survived to the present day. Moreover, to study the universe as it was at early times we must observe the most distant possible sources, since their light has traveled for the longest time to reach us. Even the largest telescopes cannot detect individual stars from the early universe, but effective techniques have been developed to measure very trace concentrations of chemicals in the cosmic web. This provides us with a powerful, indirect method to infer the existence of early stars whose light we could never hope to detect directly.

The tendrils of the web are filled with tenuous gas that does not shine on its own. However, we can still measure its properties by seeing how it influences light traveling through from faraway sources. The background object of choice for these observations is a QUASAR, an unusually active galaxy containing a supermassive black hole at its center. Gas accretion around this black hole powers intense radiation that can outshine all of the stars in the galaxy by factors of several hundred to a thousand. Because quasars are so bright, we can observe them at cosmological distances and thus trace the effects of intergalactic gas over a substantial portion of the universe.

Figure 3 shows a spectrum of the light from a distant quasar, obtained at the Magellan Telescopes in January 2005. The most striking feature in the spectrum is a strong emission spike near 6700Å; this is a signature of electron excitation in hydrogen atoms near the black hole. When these electrons are kicked out of

FIGURE 3

Spectrum of a z = 4.4 quasar, *obtained by the author at Magellan in January 2005. Top panel illustrates how the quasar would appear before transmission through the cosmic web. Middle panel shows the observed spectrum, which has been altered along its journey. Spectral regions blueward of the hydrogen emission are partially absorbed by intervening hydrogen clouds at lower redshift. These clouds are laced with chemical debris from early stars and supernovae, which can be detected as weak absorption lines to the red of the hydrogen emission. The light from this quasar was emitted when the universe was just 1.4 billion years old, or 10% of its present age.*
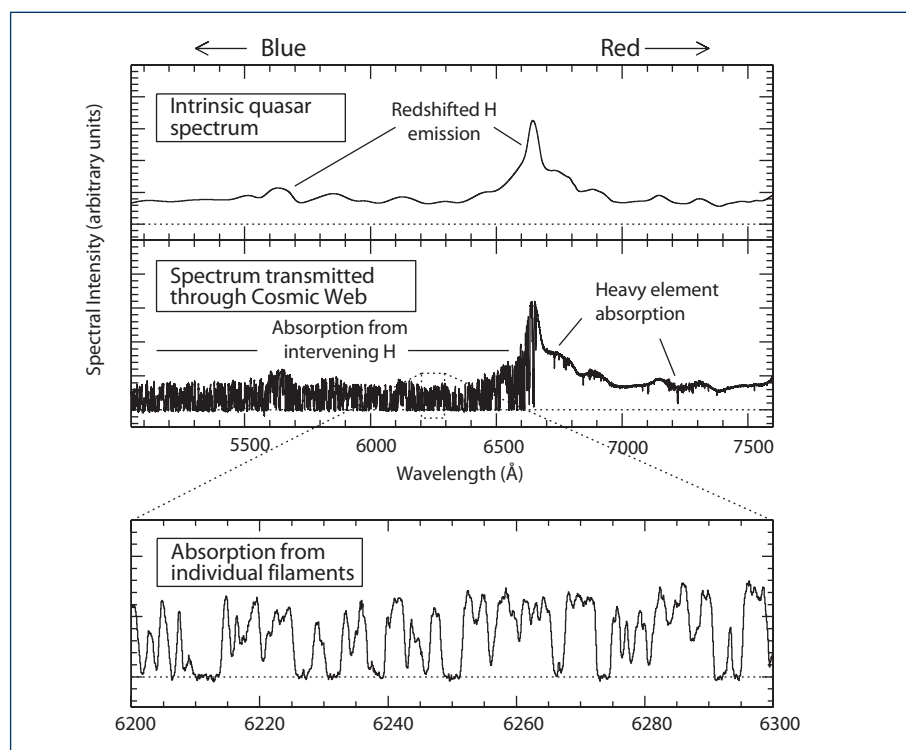
their ground state, they emit photons with λ = 1216Å as they settle back from the n = 2 to n = 1 quantum level. We observe the emission at 6700Å rather than 1216Å because the quasar is racing away from us in the general expansion of the universe following the Big Bang. This creates an effect similar to the Doppler shift: light from receding objects is pushed systematically to redder wavelengths much like the classic example of a passing train whistle's falling pitch. Astronomers parameterize this effect by assigning each object a "redshift" z, which is defined for historical reasons as

$$(1 + z) = \frac{\lambda_{\text{observed}}}{\lambda_{\text{emitted}}} \qquad (1)$$

where the emitted wavelength is measured in the lab or determined from theory. Typically we measure redshifts by comparing a whole suite of lines measured in the lab with the astronomical spectrum, to see that their wavelengths are all boosted by the same factor of $(1 + z)$. Because we live in an expanding universe, each object's recession velocity (and hence its redshift) is proportional to its distance from the Earth (see *sidebar*). Objects with large redshifts are very distant, so we see them as they were long ago when their light was emitted.

As a quasar's light travels toward Earth, it must navigate through the cosmic web, and since such large distances are covered, the light is sure to intercept many intergalactic gas clouds en route. When quasar light suffers chance encounters with neutral atoms in these clouds, the atoms absorb specific photons whose frequencies correspond to electron energy level transitions, like the n = 1 to 2 transition at 1216Å for hydrogen. This absorption creates a dark "hole" in the transmitted quasar spectrum. The cosmic web contains many gas clouds at different distances from earth. And because clouds at different distances have different redshifts, quasar spectra all exhibit a large number of discrete absorption lines, which map the 1-D distribution of gas density along the line-of-sight. Hydrogen is by far the most abundant element in the universe, so it is the source of most quasar absorption lines. This explains why the spectrum in *Figure 3* appears to be eaten away leftward of the hydrogen emission — we are seeing intergalactic hydrogen *absorption* up to the *emission* redshift of the quasar; gas at higher redshift lies behind the quasar and is thus hidden from view.
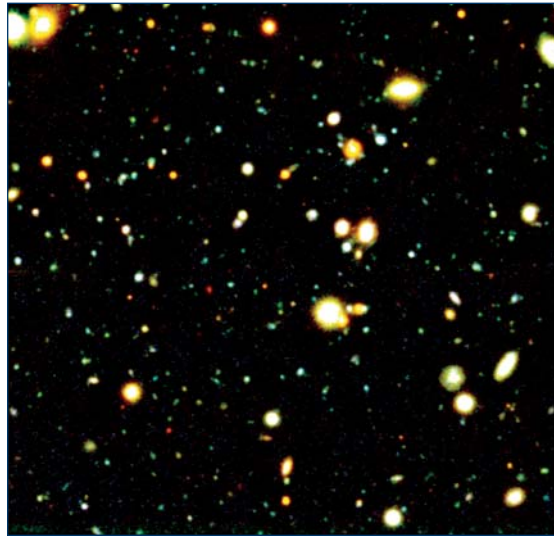
(Cosmic Redshift and the Expanding Universe (FIGURE 5)

Redshift has a deeper meaning that ties into the concept of cosmic expansion after the Big Bang. Einstein and Hubble tell us that the universe grows in four dimensions, but we can draw a mathematically equivalent analogy with just three. Imagine the universe like an inflating sphere or bubble, with all galaxies living on the surface *(Figure 5)*. The galaxies' positions on the sphere are defined by just two numbers (e.g. longitude and latitude), but the distance between any two galaxies A and B as measured along the bubble's surface increases as the bubble expands. Now consider what happens to a photon emitted from galaxy A towards an observer at galaxy B, traveling on the surface of the expanding sphere. The photon races to catch up with the increasing *linear* distance L, but the *angular* distance $[\theta]$ is a constant of the expansion. In each time interval $[dt]$, the photon travels a fixed angular distance $[d\theta = c\, dt / R(t)]$.

The photon can equivalently be considered a light wave whose periodic sinusoidal peaks are separated in time by $[\delta t_{emit},]$ so that $[c\,\delta t_{emit} = \lambda_{emit}.]$ How will the arrival pulse rate $[\delta t_{observe}]$ be stretched by cosmological expansion along its journey? We can follow the path of two successive pulses from galaxy A to B:

Pulse 1:
$$\int_0^\theta d\theta = \int_{t_{emit}}^{t_{obs}} \frac{c\, dt}{R(t)} \qquad (2)$$

Pulse 2:
$$\int_0^\theta d\theta = \int_{t_{emit}+\delta t_{emit}}^{t_{obs}+\delta t_{obs}} \frac{c\, dt}{R(t)} \qquad (3)$$

$$= \int_{t_{emit}}^{t_{obs}} \frac{c\, dt}{R(t)} + \frac{c\,\delta t_{obs}}{R(t_{obs})} - \frac{c\,\delta t_{emit}}{R(t_{emit})} \qquad (4)$$

Where we assume for the final step that $[R(t)]$ is effectively constant over the short intervals $[\delta t]$ (typically less than 10^{-14} seconds for a light wave). Since the angular integral is the same for both photons and by our definition $[c\,\delta t = \lambda]$, these equations reduce to:

$$\frac{\lambda_{observed}}{\lambda_{emitted}} = \frac{R(t_{observed})}{R(t_{emitted})} = (1+z) \qquad (5)$$

In other words, when we train our telescopes on a source with redshift z, we are observing light emitted at a time when the universe was a factor of $(1+z)$ smaller than it is today. Objects with higher redshifts emitted their light at earlier and earlier times — light from the quasar in *Figure 3* has a redshift of $z = 4.4$, so the universe has multiplied 5.4 times over in size during its journey.

However, there are also a number of weaker absorption lines to the red of the hydrogen emission. These features are caused by elements other than hydrogen, which have different electron energy configurations and hence different transition wavelengths in the lab. These "other" elements include (but are not limited to) carbon, silicon, oxygen, iron, or nitrogen: exactly the chemicals that are produced exclusively in stars! Their presence implies that the cosmic web was widely polluted with supernova debris from very early in the history of the universe. The absorption measurements are very sensitive, and the chemical concentrations are miniscule. With quasar spectra we can study gas clouds with densities of 1 atom per cubic meter at distances spanning 90% of the observable universe. Even then the hydrogen atoms outnumber heavy element atoms by a million to one. Yet even these few particles provide crucial confirmation of the presence of early stars whose light we cannot see.

Ongoing and Future Work on Cosmic Abundances

Absorption lines in high redshift quasars have revealed stellar pollutants in the intergalactic medium to z ~ 5. This is within the first billion years after the Big Bang, essentially as far back as we can look with present technology. At MIT, we have been pursuing several new research avenues relating to chemical pollution and the first stars. One approach is to study the pollution process itself, at slightly lower redshifts where we can observe the light from star forming galaxies directly *(Figure 4)*. We have been mapping the distribution of galaxies at z ~ 2.5 (roughly 80% lookback time to the Big Bang) in regions of the sky surrounding several quasars at z ~ 3 and higher. The galaxies host episodic "bursts" of star formation and supernovae, which expel heavy elements out into intergalactic space. When the outflowing debris sweeps across the quasar sightline, we can detect its presence through absorption lines and study the physical processes that govern this mixing in real-time.

Our second goal is to push the redshift frontier even further back into the past. The current generation of abundance studies relies exclusively on observations at optical wavelengths, because of sensitivity limitations

with other instruments on large telescopes. However, at z > 5, the atomic transitions of interest are redshifted to infrared wavelengths. We are in the process of constructing a sensitive new infrared spectrometer named FIRE (the Folded InfraRed Echellette) for the Magellan telescopes, which will allow us to extend these stellar forensic studies to z ~ 6 and beyond. In this era, the timescales for star and galaxy formation approach the age of the universe, so we may well be closing in on the initial epoch of "first light." Such hard-won photons and chemical traces from early stars bring to mind more words from Frost, in *Choose Something Like a Star:*

> *Use language we can comprehend.*
> *Tell us what elements you blend.*
> *It gives us strangely little aid,*
> *But does tell something in the end.*

ROBERT A. SIMCOE is a Pappalardo Fellow in Physics at the Massachusetts Institute of Technology. He specializes in observational astrophysics, with particular emphasis on the chemistry of galaxies and intergalactic matter in the early universe. An amateur astronomer and telescope maker from his youth, Simcoe went on to earn his A.B. in astrophysical sciences from Princeton in 1997, and his Ph.D. in astronomy from Caltech in 2003. He remains active in the application of new technologies toward instrumentation for large ground-based telescopes — including the twin 6.5 meter Magellan telescopes in the Chilean Andes, where he carries out most of his observations. Simcoe will be joining the MIT Physics faculty as an Assistant Professor in the fall of 2006.
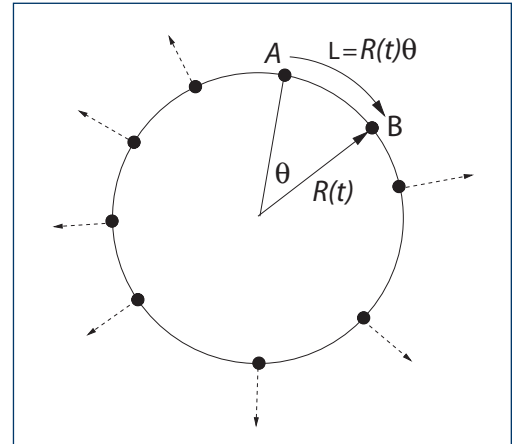

FIGURE 5

Simple geometric model of an expanding universe. Dots on the sphere represent galaxies, whose separation L grows as R(t) increases, even as the angular separation θ stays fixed.