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MISSING PAGES IN OUR PHOTO ALBUM OF THE INFANT UNIVERSE

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ABSTRACT

Existing data sets include an image of the Universe when it was 0.4 million years old (in the form of the cosmic microwave background), as well as images of individual galaxies when the Universe was older than a billion years. But there is a serious challenge: in between these two epochs was a period when the Universe was dark, stars had not yet formed, and the cosmic microwave background no longer traced the distribution of matter. And this is precisely the most interesting period, when the primordial soup evolved into the rich zoo of objects we now see. In this popular-level overview I describe how astronomers plan to observe this nearly-invisible yet crucial period.

Subject headings: cosmology

1. FIRST LIGHT

When I look up into the sky at night, I often wonder whether we humans are too preoccupied with ourselves. There is much more to the universe than meets the eye on earth. As an astrophysicist I have the privilege of being paid to think about it, and it puts things in perspective for me. There are things that I would otherwise be bothered by - my own death, for example. Everyone will die sometime, but when I see the universe as a whole, it gives me a sense of longevity. I do not care so much about myself as I would otherwise, because of the big picture.

Cosmologists are addressing some of the fundamental questions that people attempted to resolve over the centuries through philosophical thinking, but we are doing so based on systematic observation and a quantitative methodology. Perhaps the greatest triumph of the past century has been a model of the universe that is supported by a large body of data. The value of such a model to our society is sometimes underappreciated. When I open the daily newspaper as part of my morning routine, I often see lengthy descriptions of conflicts between people about borders, possessions or liberties. Today's news is often forgotten a few days later. But when one opens ancient texts that have appealed to a broad audience over a longer period of time, such as the Bible, what does one often find in the opening chapter? A discussion of how the constituents of the universe – light, stars, and life – were created. Although humans are often caught up with mundane problems, they are curious about the big picture. As citizens of the universe we cannot help but wonder how the first sources of light formed, how life came into existence and whether we are alone as intelligent beings in this vast space. Astronomers in the 21st century are uniquely positioned to answer these big questions with scientific instruments and a quantitative methodology.

It is sometimes argued that science takes away the sense of mystery about our origins. However, current scientific circumstances appear to only enhance the mystery. Consider what astronomers have learned so far about the early Universe. We have an image of the Universe at the moment that hydrogen atoms first formed in it – namely the cosmic microwave background radiation – and we have pictures of individual galaxies more than a billion years later. The intervening epoch, though, was a period that started when the Universe was dark, stars had not yet formed, and the cosmic microwave background no longer traced the distribution of matter. And this is precisely the most interesting period, when the primordial soup evolved into the rich zoo of objects we now see.

The situation is similar to having a photo album of a person that contains the first ultrasound image of him or her as an unborn baby and some additional photos as a teenager and an adult. If you tried to guess from these pictures what happened in the interim, you could be seriously wrong. A child is not simply a scaled-up fetus or scaled-down adult. The same is with galaxies. The primordial hydrogen gas was composed of atoms, so you might suppose that the Universe traced out a straightforward and rather boring path towards the assembly of atoms into galaxies. It did not. Observations of the spectra of early galaxies and quasars, which reveal the conditions in their environments, indicate that the cosmic gas actually underwent a wrenching transition from atoms back to their constituent protons and electrons – a process known as reionization. In fact, although the world around us is composed of atoms, the bulk of the Universe's ordinary matter today is still in the form of free electrons and protons, located deep in intergalactic space.

How the Universe underwent this transition is one of the most exciting questions in cosmology today. Most researchers associate the transition with the first generation of stars, whose ultraviolet radiation streamed into intergalactic space and broke atoms apart. Others conjecture that material plummeting into black holes gave off radiation on its death plunge. But as often is the case in science, new observational data is required to test which of these scenarios describes reality better.

The timing of reionization depends on astrophysical parameters such as the efficiency of making stars or black holes in galaxies, but most importantly it depends on the nature and the initial inhomogeneities of the cosmic matter. Galaxies form by a process known as gravitational instability which is seeded by the initial inhomogeneities.

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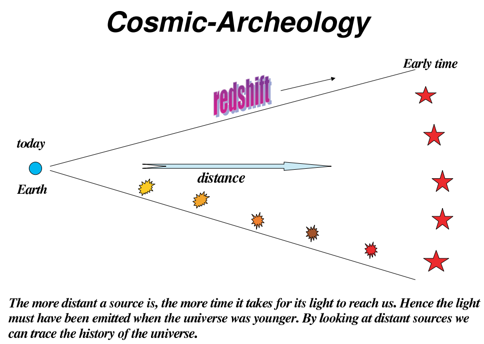

FIG. 1.— Cosmology is like archeology. The deeper one looks, the older is the layer that one is revealing, owing to the finite propagation speed of light.

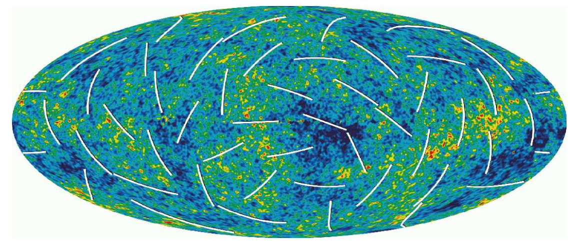

FIG. 2.— Image of the Universe at the time when it became transparent, taken by the *WMAP* satellite (see http://map.gsfc.nasa.gov/ for details). The slight density inhomogeneties at the level of one part in $\sim 10^5$ in the otherwise uniform Universe, imprinted hot and cold spots in the brightness map of the cosmic microwave background. The existence of these anisotropies was predicted in a number of theoretical papers three decades before the technology for taking this image was available. The white bars show the measured polarization direction of the background light.

A region that starts slightly denser than the average density of the Universe will tend to pull itself together by its own gravity. Although initially the region expands like the rest of the Universe, its extra gravity slows its expansion down, turns it around, and make the region collapse upon itself to make a bound object like a galaxy. Most of the cosmic matter is known to be dark, i.e. have a very weak interaction (aside from gravity) with ordinary matter and radiation. To get the process of galaxy formation started, one needs inhomogeneities in the cosmic matter distribution on the small scale of galaxies. Such inhomogeneities exist and can seed the formation of dwarf galaxies at early times only if the dark matter is made of massive particles that are initially cold. On the other hand, if the dark matter is warm, the velocity dispersion of the dark matter particles would erase inhomogeneities on small scales and prevent the formation of dwarf galaxies at early times. Existing data on the spectrum of initial inhomogeneities favors the notion that the dark matter is cold and not warm but the evidence is still preliminary. New data on the mass and formation time of the first dwarf galaxies will be able to robustly determine whether this is indeed the case. Laboratory accelerators (such as the *Large Hadron Collider*) will in parallel be able to search in the future for the hypothetical particle that makes the cold dark matter as long as it has an interaction strength comparable to the "weak interaction" of neutrinos, as expected in some particle-physics models.

According to the popular cosmological model of cold dark matter, dwarf galaxies started to form when the Universe was only a hundred million years old. Numerical simulations indicate that the first stars to have formed out of the prestine primordial gas left over from the big bang, were much more massive than the sun. Lacking heavy elements which would have cooled the gas to lower temperatures, the warm primordial gas could have only fragmented into relatively massive clumps which condensed to make the first stars. These stars were efficient factories of ionizing radiation (see the Scientific American article by Bromm & Larson). Once they exhaust their nuclear fuel, some of these stars are expected to explode as supernovae and disperse the heavy elements that were cooked by nuclear reactions in their interiors into the surrounding gas. The heavy elements cool the diffuse gas to lower temperatures and allow it to fragment into lower-mass clumps that make the second generation of stars. The ultraviolet (UV) radiation emitted by all generations of stars eventually leaked into the intergalactic space and ionized gas far outside the boundaries of individual galaxies.

The earliest dwarf galaxies merged and made bigger galaxies as time went on. A present-day galaxy like our own Milky-Way was constructed over cosmic history by the assembly of a million building blocks like the first dwarf galaxies. The UV radiation from each galaxy created an ionized bubble in the cosmic gas around it. These bubbles grew in size as the galaxies grew in mass and eventually surrounded groups of galaxies. Finally as more galaxies formed, the bubbles overlapped and the initially neutral gas in between the galaxies was completely re-ionized.

Although the above progression of events sounds plausible, its existence has been confined to the minds of theorists so far. Empirical cosmologists would like to actually see direct evidence for the reionization epoch before putting its description as a missing chapter in their textbooks. *How can one observe the reionization history of the Universe?* ... One way is by imaging hydrogen through its radio (21cm) emission and searching for the ionized bubbles in it with radio telescopes. Another way is by searching for the radiation emitted by the first galaxies with big new telescopes from the ground as well as from space. Below we will describe each of these techniques along with the theoretical work that motivates it. The study of the reionization epoch promises to be one of the most active frontiers in cosmology over the next decade.

2. COSMIC TIME MACHINE

When we look at our image reflected off a mirror at a distance of 1 meter, we see the way we looked 6 nanoseconds ago, the light travel time to the mirror and back. If the mirror is spaced 10^{19} cm = 3pc away, we will see the way we looked twenty one years ago. Light propagates at a finite speed, and so by observing distant regions, we are able to see how the Universe looked like in the past, a light travel time ago. The statistical homogeneity of the Universe on large scales guarantees that what we see far away is a fair statistical representation of the conditions that were present in our region of the Universe a long time ago.

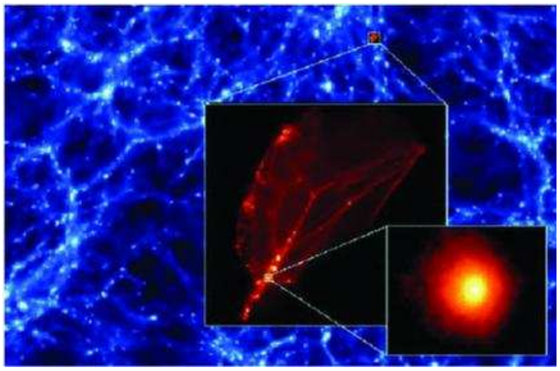

FIG. 3.— A slice through a numerical simulation of the first dark matter condensations to form in the Universe. Colors represent the dark matter density at a redshift $z = 26$. For a given redshift value z, the coefficient $(1+z)$ is the factor by which any scale in the Universe (including the wavelength of a photon) is being stretched up to the present-time. The simulated volume is 1.8×10^{20} present-day cm on a side, simulated with 64 million particles each weighing $\sim 10^{-4}$ Earth masses (!). (from Diemand, Moore, & Stadel 2005).

This fortunate situation makes cosmology an empirical science. We do not need to guess how the Universe evolved. Using telescopes we can simply see the way distant regions appeared within it at earlier cosmic times. Since a greater distance means a fainter flux from a source of a fixed luminosity, the observation of the earliest sources of light requires the development of sensitive instruments and poses challenges to observers.

We can in principle image the Universe only if it is transparent. Earlier than 0.4 million years after the big bang, the cosmic gas was sufficiently hot to be fully ionized (i.e. atoms were broken into free nuclei and electrons) and the Universe was opaque due to scattering by the dense fog of free electrons that filled it. Thus, telescopes cannot be used to image the infant Universe at earlier times (or redshifts $\gtrsim 10^3$). The earliest possible image of the Universe was recorded in the cosmic microwave background, the thermal radiation left over from the transition to transparency (see Fig. 2).

3. COMPLETING OUR PHOTO ALBUM OF THE UNIVERSE

The ultimate goal of observational cosmology is to image the entire history of the Universe since the time it became transparent. Currently, we have a snapshot of the Universe at an age of 0.4 million years from the microwave background, and detailed images of its evolution starting from an age of a billion years to the present time. The evolution between a million and a billion years has not been imaged as of yet.

Within the next decade, NASA plans to launch the successor to the Hubble Space Telescope named the James Webb Space Telescope (*JWST*) that will be able to get infrared images of the very first sources of light (stars and black holes) in the Universe, which are predicted theoretically to have formed in the first hundreds of millions of years. In parallel, there are several initiatives to construct large infrared telescopes on the ground with the same goal in mind [2], [3,4]. Independently, the neutral hydrogen left over from the big bang, can be mapped in

[2] http://www.eso.org/projects/e-elt/
[3] http://tmt.ucolick.org/
[4] http://www.gmto.org/

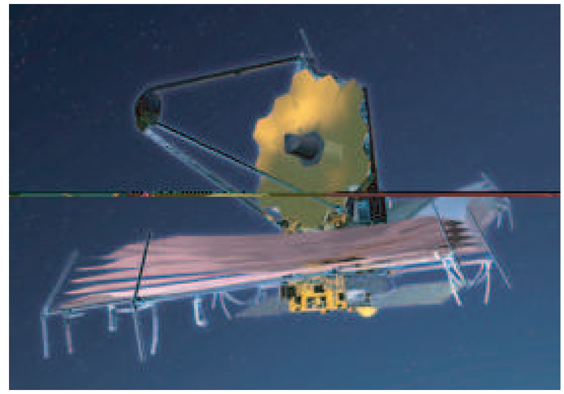

FIG. 4.— A sketch of the current design for the *James Webb Space Telescope*, successor to the *Hubble Space Telescope* to be launched in 2013 (http://www.jwst.nasa.gov/). The current design includes a primary mirror made of beryllium which is 6.5 meter in diameter as well as instrument sensitivity that spans the full range of infrared wavelengths 0.6–28μm that will allow detection of the first galaxies. The telescope will orbit 1.5 million km from Earth at the Lagrange L2 point.

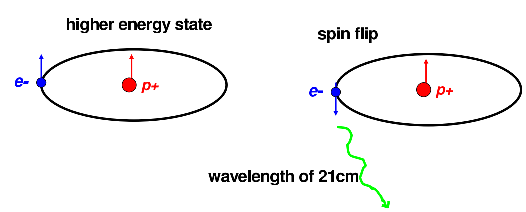

FIG. 5.— The 21cm transition of hydrogen. The higher energy level the spin of the electron (e-) is aligned with that of the proton (p+). A spin flip results in the emission of a photon with a wavelength of 21cm (or a frequency of 1420MHz).

three-dimensions through its 21cm transition even before the first galaxies formed. Several groups are currently constructing low-frequency radio arrays in an attempt to map the initial inhomogeneities as well the process by which the hydrogen was re-ionized by the first galaxies.

The wavelength of 21cm resonates with a transition of hydrogen between two states of the electron spin (splitting hydrogen's ground state) from an upper level in which the electron spin is aligned with that of the proton to the lower level where it is anti-aligned with it (see Fig. 5). The relative population of the two levels defines the so-called *spin temperature* which may deviate from the actual kinetic temperature of the gas in the presence of a radiation field. The coupling between the gas and the cosmic microwave background (owing to the small residual fraction of free electrons left over from the hydrogen formation epoch) kept the gas temperature equal to the radiation temperature up to 10 million years after the big bang. Subsequently, the cosmic expansion cooled the gas faster than the radiation and collisions among the atoms maintained their spin temperature at equilibrium with their own kinetic temperature. At this phase, cosmic hy-

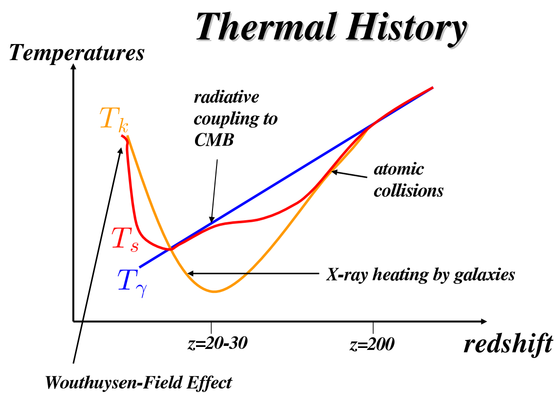

FIG. 6.— Schematic sketch of the evolution of the kinetic and spin temperature of cosmic hydrogen. Following cosmological recombination at a redshift $z \sim 10^3$, the gas temperature (orange curve) tracks the Cosmic Microwave Background (CMB) temperature (blue line; $\propto (1+z)$) down to a redshift $z \sim 200$ and then declines below it ($\propto (1+z)^2$) until the first X-ray sources (accreting black holes or exploding supernovae) heat it up well above the CMB temperature. The spin temperature of the 21cm transition (red curve) interpolates between the gas and CMB temperatures. Initially it tracks the gas temperature through atomic collisions; then it tracks the CMB through radiative coupling; and eventually it tracks the gas temperature once again after the production of a cosmic background of UV photons that redshift into the Lyα resonance (through the so-called Wouthuysen-Field effect [Wouthuysen 1952;Field 1959]).

drogen could be detected in *absorption* against the microwave background sky since it is colder. Regions that are somewhat denser than the mean will produce more absorption and vice versa. The resulting fluctuations in the 21cm brightness would simply reflect the primordial inhomogeneities in the gas. A hundred million years after the big bang, cosmic expansion diluted the density of the gas to the point where the collisional coupling of the spin temperature to the the gas became weaker than its coupling to the microwave background. At this stage, the spin temperature returned to equilibrium with the radiation temperature and it is impossible to see the gas against the microwave background brightness. Once the first galaxies lit up, they heated the gas (mainly by emitting X-rays which penerated the thick column of intergalactic hydrogen) as well as its spin temperature (through UV photons which couple the spin temperature to the gas kinetic temperature). The increase of the spin temperature beyond the microwave background temperature requires much less energy per atom than ionization, and so this heating occured well before the Universe was reionized. Once the spin temperature had risen above the microwave background temperature the gas can be seen against the microwave sky in *emission*. At this stage, the hydrogen distribution is punctuated with bubbles of ionized gas which are created around the galaxies. Mapping of the hydrogen distribution up to the completion of reionization is expected to reveal structures similar to those found by slicing swiss cheese (see Fig. 7).

The 21cm wavelength of a photon emitted at some early cosmic time is stretched by the cosmic expan-

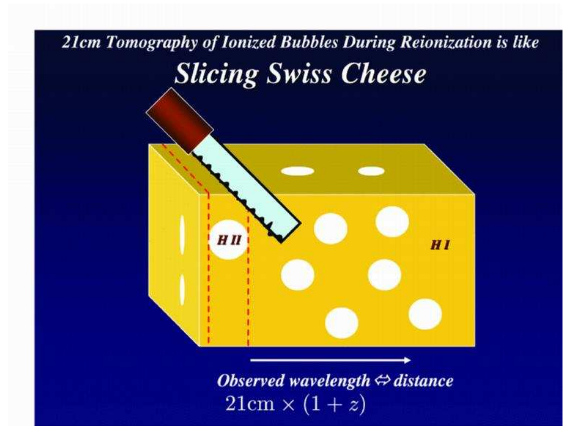

FIG. 7.— 21cm imaging of ionized bubbles during the epoch of reionization is analogous to slicing swiss cheese. The technique of slicing at intervals separated by the typical dimension of a bubble is optimal for revealing different pattens in each slice.

sion since that time. The wavelength observed today is therefore larger than 21cm by a factor greater than unity which we may express as $(1+z)$, where the excess stretch z is the so-called *cosmological redshift* (named after its tendency to shift blue photons with a short wavelength towards the red where the wavelength is longer). A source at a greater distance requires an earlier emission time due to the light propagation delay, providing more wavelength stretching by the cosmic expansion, and hence a higher redshift. We know that reionization must have ended by the time that the Universe was a billion years old, and so there is no point in attempting to image diffuse hydrogen at later times. These late times correspond to redshifts below 6 or a wavelength below $(1+6)\times 21 = 147$cm, corresponding roughly to the height of a teenager.

Detection of the redshifted 21cm emission by hydrogen will be made possible with arrays of low-frequency antennas, similar to those used for television and radio communication. By shifting in observed wavelength, these antenna will be slicing the Universe at different redshifts, i.e. different distances. The combination of all the slices would provide a three-dimensional map (i.e. tomography) of the neutral hydrogen distribution. Figure 8 shows the antenna module of one of the experiments being constructed right now, the Mileura Wide-Field Array (MWA; http://web.haystack.mit.edu/arrays/MWA/). Other experiments whose goal is to detect 21cm fluctuations from the epoch of reionization at $z \sim 6-12$ include *LOFAR* (*http://www.lofar.org*), the 21CMA (formerly known as the Primeval Structure Telescope [*PAST*; *http://arxiv.org/abs/astro-ph/0502029*]), and in the more distant future the Square Kilometer Array (*SKA*; *http://www.skatelescope.org*).

The 21cm mapping of cosmic hydrogen may potentially carry the largest number of bits of information compared to any other survey method in cosmology. In particular, it has the potential to provide a much richer data set than the well-established method of mapping the brightness fluctuations of the cosmic microwave background across the sky. While the latter provides a two-dimensional image of the surface where the microwave photons originated (corresponding to the time when the Universe became transparent), the redshifted 21cm photons map the hydrogen distribution in *three dimensions*. These dimensions include the two sky coordinates and the observed wavelength, which is equivalent to distance because larger distances are associated with longer light travel time and more stretching of the initial 21cm wavelength of the photons by the cosmic expansion. Second, the fluctuations of the microwave background are known to be damped on small scales, because the microwave photons diffuse across small distances and erase the primordial fluctuations on these scales. On the other hand, the 21cm photons originate from a resonant transition of hydrogen atoms and so they trace the gas distribution on all scales. The gas is expected to be inhomogeneous on all scales down to where pressure counteracts gravity and smoothes the inhomogeneities through sound waves. As it turns out, this minimum clumping scale for the gas is many orders of magnitude smaller than the diffusion scale of the microwave background photons. Consequently, the 21cm photons can trace the primordial inhomogeneities with a much finer resolution (i.e. many more independent pixels) than the microwave background. Third, the microwave background fluctuations originated at an early time before the first galaxies formed in the Universe and so they mainly carry information about the small seed inhomogeneities that existed in the early Universe. The 21cm fluctuations probe these inhomogeneities as well as the bubbles of ionized gas around groups of galaxies (in the form of cavities in the distribution of neutral hydrogen). Hence the 21cm data could inform us about the initial conditions of the Universe as well as on the environmental impact of the first galaxies on their cosmic habitat.

Why is it then that 21cm mapping of the infant Universe was not done already? Detection of the redshifted 21cm signal is challenging. Low-frequency foreground from radio broadcasting on Earth can be eliminated by frequency filtering techniques and most importantly by choosing wisely the observatory site. However, it is impossible to avoid the fact that relativistic electrons within our Milky-Way galaxy produce synchrotron radio emission as they gyrate around the Galactic magnetic field. This produces a radio foreground that is at least a factor of ten thousand larger than the expected reionization signal. But not all is lost. By shifting slightly in observed wavelength one is slicing the hydrogen distribution at different redshifts and hence one is seeing a different map of its bubble structure, but the synchrotron foreground remains nearly the same. Theoretical calculations demonstrate that it is possible to extract the signal from the epoch of reionization by subtracting the radio images of the sky at slightly different wavelengths.

In parallel to the search for redshifted 21cm fluctuations, future infrared telescopes will search directly for the early galaxies that induced some of these fluctuations. The next generation of ground-based telescopes will have a diameter of 24-42 meters (examples include the *Giant Magellan Telescope*, the *Thirty Meter Telescope*, and the *European Extremely Large Telescope*). Together with the infrared space telescope JWST (that will not be affected by the atmospheric opacity and emission), they will be able to image the first galaxies. Given that these galaxies also created the ionized bubbles around them, the locations of galaxies should correlate with bubbles in the neutral hydrogen. Within a decade it would

FIG. 8.— Prototype of the tile design for the *Mileura Wide-Field Array* (MWA) in western Australia, aimed at detecting redshifted 21cm from the epoch of reionization. Each 4m×4m tile contains 16 dipole antennas operating in the frequency range of 80–300MHz. Altogether the initial phase of MWA (the so-called "Low-Frequency Demostrator") will include 500 antenna tiles with a total collecting area of 8000 m^2 at 150MHz, scattered across a 1.5 km region and providing an angular resolution of a few arcminutes across the sky.

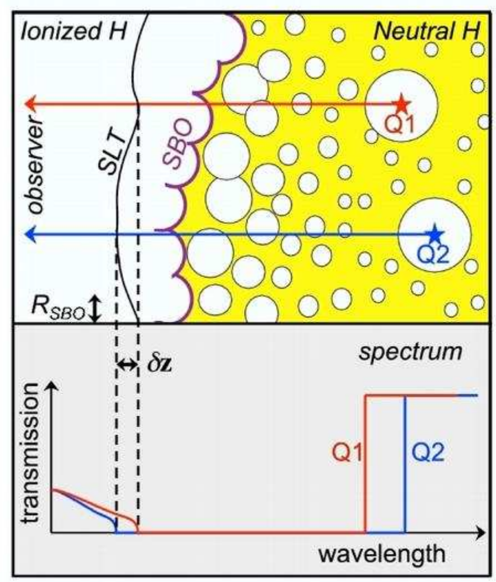

FIG. 9.— The distances to the observed Surface of Bubble Overlap (SBO) fluctuate on the sky (from Wyithe & Loeb 2004). The SBO corresponds to the first region of diffuse neutral hydrogen *observed* along a random line-of-sight. It fluctuates across a shell with a minimum width dictated by the condition that the light crossing time across the characteristic radius $R_{\rm SBO}$ of ionized bubbles equals the cosmic scatter in their formation times. After some time delay the ionized cosmic gas becomes transparent to Lyα photons (which resonate with the transition of hydrogen from its ground state to the first excited level), resulting in a second surface, the Surface of Lyα Transmission (SLT). The upper panel illustrates how the lines-of-sight towards two quasars (Q1 in red and Q2 in blue) intersect the SLT with a redshift difference δz. The resulting variation in the observed spectrum of the two quasars is shown in the lower panel.

FIG. 10.— Artist conception of the design for one of the future giant telescopes that could probe the first generation of galaxies from the ground. The *Giant Magellan Telescope* (GMT) will contain seven mirrors (each 8.4 meter in diameter) and will have the resolving power equivalent to a 24.5 meter (80 foot) primary mirror. For more details see http://www.gmto.org/

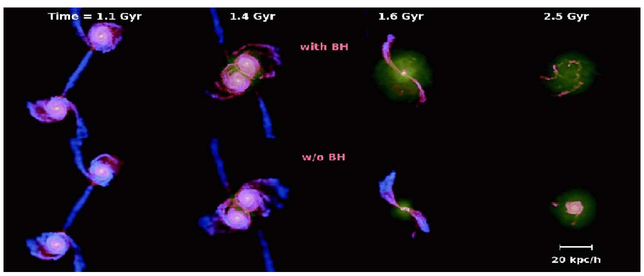

FIG. 11.— Simulation images of a merger of galaxies resulting in quasar activity that eventually shuts-off the accretion of gas onto the black hole (from Di Matteo et al. 2005). The upper (lower) panels show a sequence of snapshots of the gas distribution during a merger with (without) feedback from a central black hole. The temperature of the gas is color coded.

be possible to explore the environmental influence of individual galaxies by using both radio and infrared instruments in concert.

4. BUT THE BRIGHTEST SOURCES ACROSS THE UNIVERSE ARE NOT GALAXIES!

As already mentioned, imaging the infant Universe would reveal how the building blocks of present-day galaxies originated. Of particular interest is the formation history of massive black holes in the centers of these galaxies. It has been recently realized that almost every galaxy in the present-day Universe hosts a massive black hole at its nucleus. In our own Milky-Way galaxy, stars were found to zoom around the Galactic center with speeds of up to ten thousand kilometers per second which could only be induced by a massive object which is as compact as a black hole. The nuclear black holes in galaxies are believed to be fed with gas in episodic events of gas accretion which are triggered by mergers of galaxies. The energy released by the accreting gas during these episodes could easily unbind the gas reservoir from the host galaxy and suppress star formation within it (see Fig. 11). If so, nuclear black holes regulate their own growth by expelling the gas that feeds them, and in so doing they also shape the stellar content of their host galaxy. Such feedback has been invoked to explain the observed correlation between the masses of black holes and the properties of the galaxy (most importantly, the depth of its gravitational potential well)

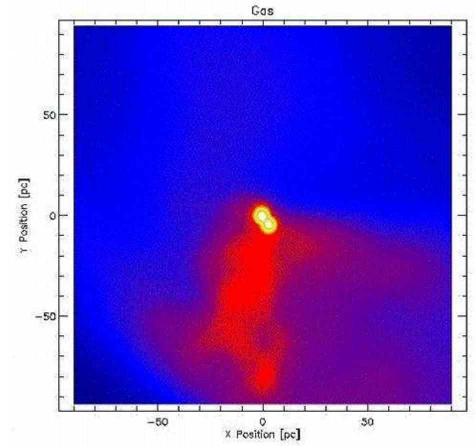

FIG. 12.— Numerical simulation of the collapse of an early dwarf galaxy with a virial temperature just above the cooling threshold of atomic hydrogen and no H_2 (from Bromm & Loeb 2003). The image shows a snapshot of the gas density distribution 500 million years after the big bang, indicating the formation of two compact objects near the center of the galaxy with masses of $2.2 \times 10^6 M_\odot$ and $3.1 \times 10^6 M_\odot$, respectively, and radii < 1 pc. Sub-fragmentation into lower mass clumps is inhibited because hydrogen atoms cannot cool the gas significantly below its initial temperature. These circumstances lead to the formation of supermassive stars that inevitably collapse and trigger the birth of supermassive black holes. The box size is 635 light years across.

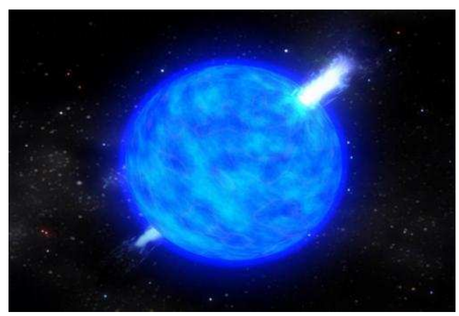

FIG. 13.— Illustration of a long-duration gamma-ray burst in the popular "collapsar" model. The collapse of the core of a massive star (which lost its hydrogen envelope) to a black hole generates two opposite jets moving out at a speed close to the speed of light. The jets drill a hole in the star and shine brightly towards an observer who happened to be located within with the collimation cones of the jets. The jets emenating from a single massive star are so bright that they can be seen across the Universe out to the epoch when the first stars have formed. Upcoming observations by the *Swift* satellite will have the sensitivity to reveal whether the first stars served as progenitors of gamma-ray bursts (for updates see http://swift.gsfc.nasa.gov/).

in which they are embedded. During their episodes of growth, the accreting gas shines much brighter than the entire galaxy surrounding it and appears as a quasar. Quasars are often a hundred times more luminous than their host galaxy. Deep observations by the *Sloan Digital Sky Survey* have revealed that quasars with black holes masses of more than a billion suns already exist in the Universe when it had only 6% of its present-age. These masses are comparable to the most massive black holes found today. *How did such massive black holes come to exist so early? Why don't we observe black holes with much higher masses today?* The answers to these questions could be found by imaging the early Universe.

Explosions of individual massive stars (known as supernovae) can also outshine their host galaxies for brief periods of time. The brightest of these explosions show up as *gamma-ray bursts*, namely bright flashes of high-energy photons followed by afterglows at lower photon energies. These afterglows can be used to study the first stars, one star at a time (see Fig. 13). Together with quasars they can also be used as beacons of light that reveal the state of the cosmic gas along the line-of-sight to them through its imprint of absorption lines on their spectra. The earliest gamma-ray burst was discovered by the recently launched *Swift* satellite. It originated at the same epoch (redshift of $z = 6.3$) as the earliest quasar (redshift of $z = 6.4$), only a billion years after the big bang. Detection of even earlier gamma-ray bursts will open a new window into the infant Universe where our origins lie.

Additional Reading

First Light. *A. Loeb, extensive review (157 pages long) prepared for the SAAS-Fee winter school, 2006; http://arxiv.org/abs/astro-ph/0603360*

The First Stars. *V. Bromm and R. Larson, Annual Reviews of Astronomy and Astrophysics, Vol. 42, pages 79-118, 2004; http://xxx.lanl.gov/abs/astro-ph/0311019*