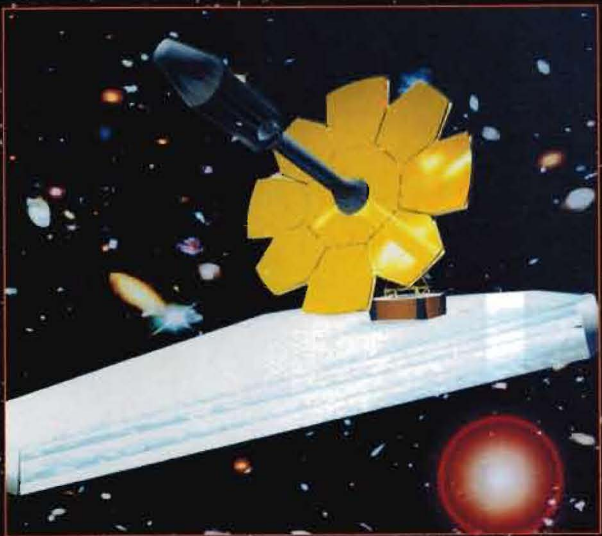
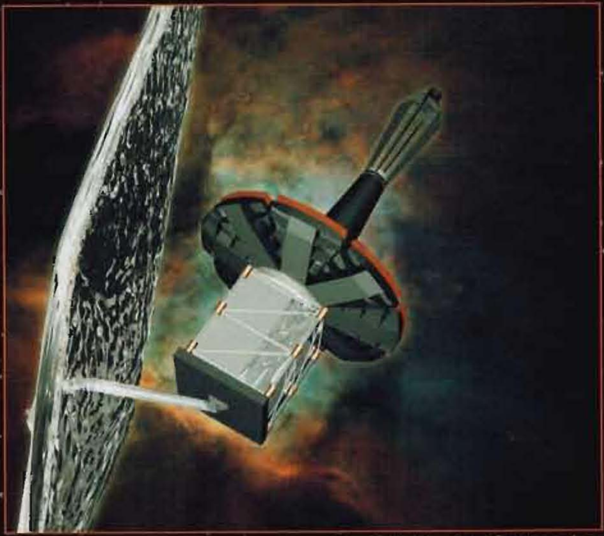
THE NEXT GENERATI

PREDICTIN

Ball Aerospace NGST Design



Goddard Space Flight Center NGST Design

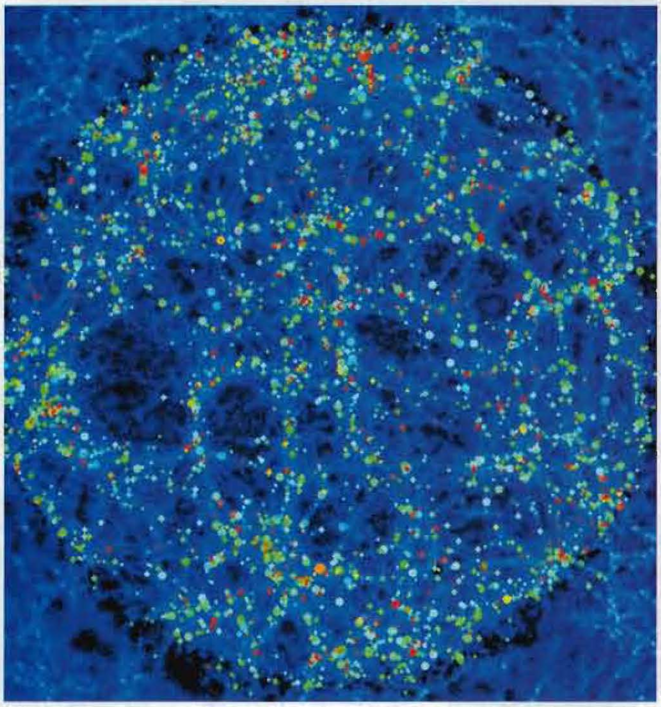


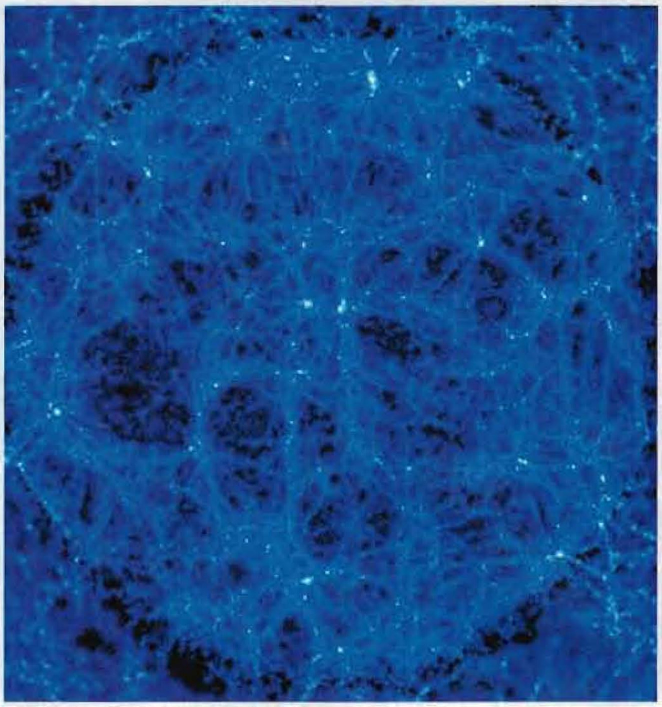
Lockheed-Martin NGST Design

ON SPACE TELESCOPE
G THE PAST

Astronomers try to foretell what will be found by the next great scope in space.

by Marcia Bartusiak





Galaxies in the local universe form on the frothy waves of dark matter in these supercomputer simulations made by the Virgo Consortium near Munich. Max-Planck Institute for Astronomy, Garching

Princeton astrophysicist Edwin Turner knows how risky it can be to predict how the universe evolved. Twenty-one years ago he attended a conference set up to speculate on the wonders to be seen with an optical telescope launched into space, what later became the Hubble Space Telescope. The predictions, says Turner, were both surreal and irrelevant.

Hubble revealed a distant universe far more vigorous and energetic than anyone ever dreamed of two decades ago. With their space-age eyes, astronomers were able to look outward more than halfway across the visible universe. In 1979 theorists had expected nearly all the galaxies there (except for the occasional and rare quasar burning fiercely) to look pretty much the same as those around us today — the same classical spirals and ellipticals only brighter and bluer. Instead, many of the young galaxies were found to be disturbed, messy, and shaken up.

Astronomers are still trying to sort it all out. Yet, despite the flawed predictions made 21 years ago, many of the world's experts on the early universe gathered at Harvard University to once again discuss what they might find as a new generation of telescopes, both in space and on the ground, comes on-line this decade.

With these new instruments, astronomers will be reaching back to what might be called the "age of enlightenment," the era when stars and galaxies first formed. It is a key period in the universe's evolution.

Seeing the First Stars

For the first 300,000 years or so after the Big Bang, the universe was hot and bright as matter and radiation commingled. But as soon as electrons combined with protons to form atomic hydrogen and atomic helium, the radiation was released to wander for a while through the gas.

With matter cooling down and the radiation becoming dim and diffuse, the cosmos entered what Martin Rees of Cambridge University, Great Britain's Astronomer Royal, refers to as the "dark ages." These dark times didn't end and the bright times begin again until the birth of stars, their nuclear fires at last lighting up the universe with spectacular splendor.

It was the beginning of a tumultuous era: When stars are born, some also quickly die, generating supernovae that spread a star's ashes of heavier elements through the cosmos. The shock waves move through the gas to assist the formation of new stars — and at prodigious rates. Supermassive black holes begin assembling in galactic cores, turning on as brilliant quasars as they "eat" the rich supplies of primordial gas. The universe, being smaller in its youth, is also more crowded, which leads to many galaxy mergers. Perhaps that explains the strange shapes seen in the distant and thus young galaxies.

To know for sure, though, requires special eyesight. As the universe expands, the light within it gets stretched along the way — shifted toward the red end of the spectrum. Astronomers keep track with a redshift scale called "z." A z of 0 — no change at all — is the present day. A z of 1 denotes the shifted light originated at a time roughly halfway back to the Big Bang. A z of 2 is 76 percent of the way back, a z of 5 about 91 percent. (See box, page 43.) By the time the light waves emitted from the earliest galaxies have reached Earth, they have appreciably lengthened. Due to the redshift, the visible radiation emitted by the first stars has stretched into infrared wavelengths.

Hence the intense interest in the Next Generation Space Telescope, the Hubble's planned successor. It is U.S. astronomy's top priority for the coming decade. Using some kind of flexible material described at the conference as "thin as a dinner plate" (nickel, special glasses, and silicon carbide are being studied), the NGST will unfurl a mirror as much as 26 feet across. (The Hubble's more traditional mirror is just under 8 feet in width.) NGST will be designed to gather the faint infrared waves from the distant universe as far out as a redshift of 20, when the universe was a mere 200 million years old. With such power, astronomers will be able to see the dark ages come to an end and directly observe how the universe created its first luminous structures. If all goes as planned, the NGST could be up and running by 2009.

On the ground, new millimeter and submillimeter arrays will complement the exploration by gathering radio waves that can pass through intervening dust, allowing astronomers to examine young galaxies that might otherwise be obscured by their dusty envelopes. At the same time, the success of the two Keck telescopes, each with mirrors 33 feet wide, is driving enthusiasm for building ELTs, or extremely large telescopes with mirrors 100 feet or more across. Such telescopes would let astronomers carry out the sensitive spectrographic work needed to decipher the faint spectral clues arriving from the distant cosmos. Together, these varied instruments could probe the history of galaxy formation.

"Astronomy's slogan may be 'observers lead the way,' " noted Harvard astrophysicist and conference organizer Abraham Loeb in his opening remarks, "but theorists instruct them where to go." And theorists start by figuring out what the first structures in the universe might look like. Simon White, a veteran at this game for some two decades and now based at the Max Planck Institute for Astrophysics in Munich, reported on the latest results obtained by the Virgo Consortium, an international group organized to carry out supercomputer simulations of the universe's large-scale structure.

Consortium members start with a few basics. From observational evidence, they assume that most of the matter in the universe consists of a mysterious dark matter, possibly a slew of yet-to-be-discovered elementary particles known as WIMPs, for weakly interacting massive particles. Tiny density fluctuations, seen in the cosmic microwave background, cause this dark matter to start clumping. Inside the computer many eons tick away and what results over time is a spongelike structure. Through the work of gravity, the dark matter comes to be concentrated in fat threads that weave through the universe, with vast voids situated in-between.

Finding the Right Blend

More recently the Virgo team has been adding ordinary matter, the stuff of stars and galaxies, into this dark matter. This gas, as expected, eventually separates from the dark matter and begins to condense into disks. The disks merge to make spheroid bulges. The gas can even settle down around some of these bulges to make new disks. Where gas is sparse, few galaxies are made. More galaxies form in the densest regions. In this way, Virgo team members try to duplicate what is seen in the present-day universe. "We get a rough fit," said White.

In one particular simulation, they even had clusters of galaxies that look very much like the prominent clusters near us today, such as the Coma, Virgo, and Centaurus clusters. Moreover, these simulated clusters were seen to form fairly early, matching what observations suggest. Using the Keck telescopes, Caltech astronomer Charles Steidel has been reaching farther and farther out into the universe, out to a redshift of 5. Already at a z of 2.5 to 3.5 he sees indications of strong galaxy clustering. There are already hints that high redshift quasars, too, are predominantly arranged in large structures. The Sloan Digital Sky Survey, now mapping the celestial sky with a dedicated 2.5-meter telescope at Apache Point Observatory in the Sacramento Mountains of New Mexico, is discovering dozens of new quasars. The farthest ones are strongly clustered.

Such successes give theorists the courage to speculate on other questions. How did stars first form within those primordial structures built out of dark matter? When did star formation get started? How did it then evolve, and were those early stars similar to the ones being made today, say in the Orion Nebula?

For the moment, theory suggests those first stars had to be different. For one, they would be burning pure hydrogen and helium. The heavier elements were not yet cooked up. Such conditions tell theorists that the first stars had to be heftier than the average star today, since the hotter core of a massive star may be required to carry out nuclear fusion with hydrogen and helium alone. Each star might contain the mass of a hundred or more of our suns. Such stars would live and die relatively quickly, a few million years or so, and emit copious amounts of ultraviolet radiation.

According to some current theoretical models, the first stars would begin to condense once there were dark-matter clumps in the universe weighing at least a million solar masses, the sorts of objects the Virgo consortium sees in its simulations. Such a clump produces a big enough gravitational "well" for the primordial hydrogen and helium dispersed throughout the dark matter like an added spice (about 100,000 solar masses) to be attracted inward and begin to cool to form star-sized objects.

Tom Abel, an astrophysicist at the Harvard-Smithsonian Center for Astrophysics, took conferees on a tour of the birthing process with a computer simulation that he had conducted with his collaborators Greg Bryan of MIT and Michael Norman of the University of Illinois. Starting with a uniform mix of primordial dark matter and gas, they followed its gravitational collapse over time. By a redshift of 20 or 30, about 100 million years after the Big Bang, the first star is born.

Step by step, Abel zoomed in to display the inner structure of a dark-matter clump. At a range of 2,000 light-years, a sort of protogalaxy is observed. The gas by now has fallen

How Far to the Big Bang?

Redshift	Dis. from BB	% of Dist.	Distance
0	13.5 billion ly	0	0 ly
0.5	8.4 billion	37	5.1 billion
1	5.8 billion	57	7.7 billion
2	3.2 billion	76	10.3 billion
3	2.1 billion	84	11.4 billion
5	1.2 billion	91	12.3 billion
7	750 million	94	12.7 billion
10	465 million	97	13 billion
15	265 million	98	13.2 billion
20	177 million	99	13.3 billion
infinity	0	100	13.5 billion

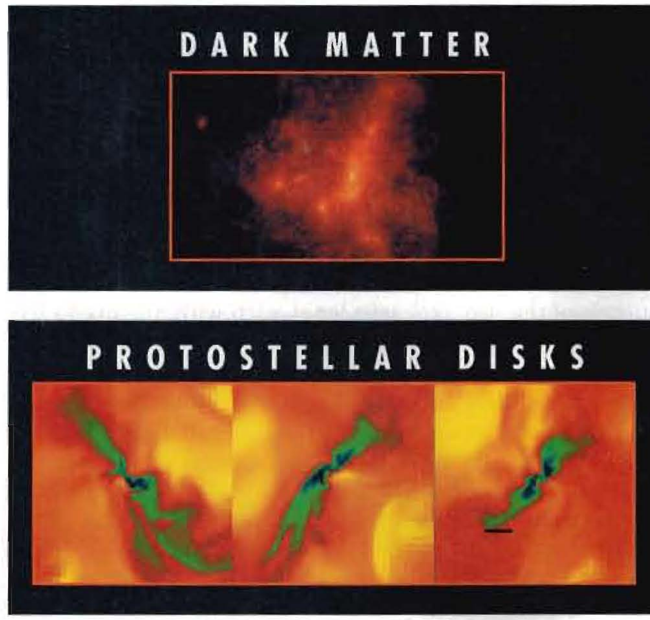
These numbers can vary depending on the cosmological model and parameters chosen. This table was calculated assuming that the Hubble constant is 70 km/sec/Megaparsec and that the universe is right on the border between open and closed, with matter contributing a third of the critical density and a cosmological constant making up the rest.

inward and settled into the center, surrounded by the halo of dark matter. Zooming inward to a scale of 200 light-years, a dense cloud is detected in the center.

Going further down to a range of two light-years, an even denser core is observed with temperatures rising to 1,000° kelvin. It contains some 200 solar masses. In the center of this core, spread over a region the width of seven solar systems, is a protostellar disk of material that will become the "first star." The innermost part contains one solar mass of material but with a gaseous envelope of 100 solar masses that may continue to accrete.

The simulation suggests that only one primordial star can form at first in any single dark-matter halo. The star's fierce ultraviolet radiation inhibits the formation of any other stars in the cloud. "Any other star that wants to form," says Abel, "may have to wait until the first one dies. That is one of the interesting results from the simulations." But is that realistic? "We're far from figuring out star formation," cautioned Princeton's Turner. The simulations so far depict a relatively gentle infalling of gas.

"We see here in the Milky Way that it's a messy process," notes Turner. And so many questions are still left unanswered. Since the gas heats up as it falls inward, how does the protostar continue to cool and condense to make the final star? It's partly done as the individual hydrogen atoms join to form molecular hydrogen, which allows some heat to be released. But how this cooling continues as the protostar turns into a star is not yet fully understood.



Harvard astrophysicist Tom Abel's computer simulations of the first stars investigate how dark matter clumps into disks. Tom Abel/Harvard

Simulating the First Stars

Volker Bromm at Yale has also carried out simulations of a primordial star's birth. He arrived at the conclusion that the first stars might have been very massive indeed, possibly as many as 1,000 solar masses. Could some of them have been the seeds, he asked, for the supermassive black holes found in quasars later on? Jerry Ostriker of Princeton estimates that the Milky Way contains some 10 million stars from that first epoch of star formation, stars with low enough masses to not blow up but rather slowly simmer over the eons. Their positions would trace the primordial halo of our galaxy. "This makes them worth looking for," says Ostriker.

The first stars were initially surrounded by neutral hydrogen, a gas that is opaque to ultraviolet light, the primary radiation emitted by massive newborn stars. In other words, the ultraviolet radiation couldn't get through. It was continually absorbed by the hydrogen, which thus acted as a screen to prevent us from observing this era. But the birth of stars marked a dramatic transition for the universe. Their very presence drastically alters the cosmic environment.

Once a star forms, it begins to ionize the hydrogen surrounding it. The star's intense radiation strips off the hydrogen's electron. This is an important process in the universe's history. Once the hydrogen is ionized, it is no longer a barrier to ultraviolet radiation. The photons can fly through such a medium freely. In this way the universe becomes open for inspection. Astronomers call it the "epoch of reionization." (It's called "reionization" because the early universe, before the dark ages began, had once before been hot and ionized.)

When did this begin? Examining the spectra of the farthest known quasars, around a redshift of 6, astronomers can tell that the universe was already highly ionized by that time. So, the process had to begin earlier. But not too early: Reionization couldn't have started before a redshift of 30, for example, because that would have diminished the fluctuations seen in the cosmic microwave background. Nickolay Gnedin of the University of Colorado believes reionization may have begun in earnest around a redshift of 15.

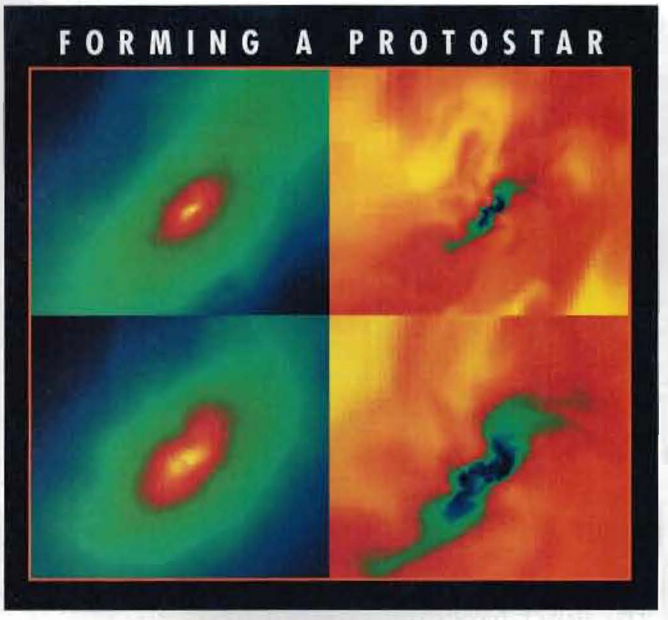
And what happens at that point is a fascinating tale. A computer-generated movie that Gnedin produced showed the process in beautiful detail. (It can be seen at http://casa.colorado.edu/~gnedin/gallery.html.) He started with a slice of the universe some 20 million light-years across. Stars are born and begin to heat up the neutral hydrogen, creating bubbles of ionized hydrogen around the star-bursting protogalaxies.

A patchwork of bubbles peppers the screen, resembling a slice of Swiss cheese. Over time, though, these pockets of ionization gradually expand throughout intergalactic space, until they merge with neighboring ones. What results is a universe suddenly clear of obscuring neutral gas.

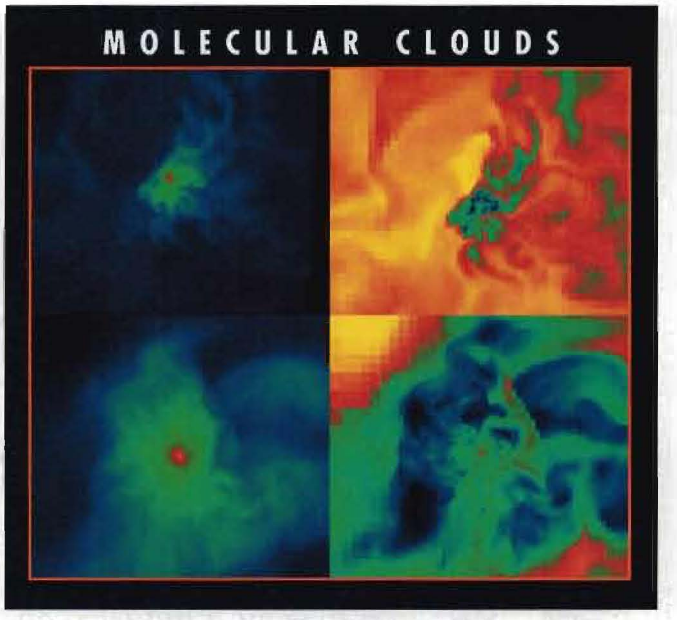
The merger of the bubbles is a very abrupt and dramatic transition. Astronomers call it the "ionization breakthrough." In Gnedin's simulation, it occurs around a redshift of 7. The entire process — from first reionization to final breakthrough — may take a relatively short time, as cosmic events go. Theorists estimate several hundred million years or so. "If the universe is a 50-year-old person," suggests Gnedin, "then reionization took place when he or she was two years old and lasted for two months." Quasars, with their intense energies, probably helped the ionization along, but these theorists believe the bulk of the work was done by stars.

With the right instrumentation, astronomers have a chance of observing the epoch of reionization directly. While ultraviolet radiation is blocked by neutral hydrogen gas, radio waves are not. If radio waves can be gathered from that distant era, astronomers will be able to witness the ionization bubbles growing and connecting.

Such an observation would be a tour de force. It would be like discerning a whisper from across the hall at an over-amplified rock concert. Strong local signals, like the many



Abel next creates a look at how the first stars might have gravitationally collapsed at the centers of these disks.



Though he can simulate them by supercomputer, the first stars may only be seen in the echos of ancient molecular clouds.

radio waves here in our own Milky Way Galaxy, would first have to be filtered out. To accomplish such a feat will require a radio telescope whose total collecting area is one square kilometer. Such a detector — called appropriately enough the Square Kilometer Array — has already been proposed and is now under study by an international consortium of astronomers.

At the moment the participants are discussing having anywhere from 100 to 1,000 separate antennae. As many as half of them might be set within 30 miles of one another in a remote area, such as the U.S. southwest or western Australia; the rest could be scattered over hundreds of miles or even over the globe. But collectively they would act as one huge telescope.

The Future of Stars Past

Harvey Butcher of the Netherlands Foundation for Research in Astronomy reported that such an array would have a hundred times the sensitivity of current radio telescopes like the Very Large Array in New Mexico or the Arecibo Observatory in Puerto Rico. "The sky would change dramatically," said Butcher. It would allow astronomers to see the first structures in the cosmos form and evolve, as well as observe star formation over the entire history of the universe.

Once star formation is underway — with stars actively cooking up the heavier elements in their interiors — a galaxy can get quite dusty. Dust particles, microscopic grains of such elements as carbon and silicon spewed into space upon a star's death, can rapidly obscure a galaxy. Its radiation is absorbed by the dust and then re-radiated at longer wavelengths. Most of this light from distant, dusty galaxies can be redshifted into the submillimeter region.

Hence, theorists are greatly interested in the new instruments about to turn on to explore this region, such as the Submillimeter Array on Hawaii's Mauna Kea. This array consists of eight dishes spread over a third of a mile. But that's only the start. A U.S.-European collaboration is planning to build the Atacama Large Millimeter Array (ALMA) on a high plateau in the Andes Mountains of Chile. ALMA might have up to 64 dish antennae dispersed over a six-mile-wide area.

A smaller detector called SCUBA (for submillimeter common-user bolometer array) working on the James Clerk Maxwell telescope at Mauna Kea already has imaged distant objects that resemble the ultraluminous infrared galaxies seen here in our local galactic neighborhood. These nearby "ULIGs" usually turn out to be galaxies merging. This generates huge bursts of star formation, hundreds of times greater than the Milky Way's production rate. If the SCUBA objects are ULIGs, this opens up the possibility that a substantial fraction of the star formation in the distant universe could be hidden by dust.

But SCUBA offers only a coarse picture. The distant objects seen in the submillimeter region might also be active galactic nuclei. The Submillimeter Array would sharpen the image and help decide what is truly happening in the far universe, perhaps as far out as a redshift of 10. Until then, theorists can only guess.

One month before the launch of the Hubble Space Telescope in 1990, a group of astronomers was asked to imagine what might be seen in the telescope's longest exposure, the type of picture that was eventually made and called the Hubble Deep Field. The astronomers at the time carried out a simulation, based on their best working knowledge of how the early universe behaved.

The picture they produced was fairly bland. Their distant galaxies were dim and sparse. The real Hubble Deep Field, on the other hand, turned out to be chockablock with colorful objects, large and small, pale and bright. "That should give us pause," said Edwin Turner at the end of the conference. "People ten years from now may find our predictions just as quaint."

Marcia Bartusiak is an accomplished science writer and member of Astronomy*'s editorial advisory board. Her latest article was "Astronomy Careers Beckon," November 2000.*