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Galaxy Evolution Explorer To Look Back In Time

by Christopher Martin

NASA's Galaxy Evolution Explorer, launched April 28, 2003, carried into space an orbiting telescope that is observing millions of galaxies across 10 billion years of cosmic history to help astronomers determine when the stars and elements we see today had their origins.

From its orbit high above Earth, the spacecraft will sweep the skies for 28 months using state-of-the-art ultraviolet detectors. Looking in the ultraviolet will single out galaxies dominated by young, hot, short-lived stars that give off a great deal of energy at that wavelength.

"The Galaxy Evolution Explorer is crucial to understanding how galaxies, the basic structures of our universe, form and function," said Dr. Ed Weiler, associate administrator for space science at NASA Headquarters, Washington. "Its ultraviolet observations will round out the knowledge we gain from observations in infrared and other wavelengths."

Astronomers believe the universe originated 13 billion to 14 billion years ago in a cataclysmic event called the Big Bang. Galaxies, the basic building blocks of the universe, began to appear as the fireball of hydrogen and helium gas that was the early universe expanded and cooled.

Glimpses of the early universe provided by the Hubble Space Telescope show that galaxies in the early stages of formation appear quite different from mature galaxies like our own Milky Way. Galaxies have undergone dramatic evolution over time; the Galaxy Evolution Explorer will study this evolution. Recent observations suggest that star formation in the universe peaked some 8 billion to 10 billion years ago. The mission is specifically designed to investigate whether this occurred and why.

The centerpiece of the spacecraft is a 50-centimeter-diameter (19.7-inch) telescope equipped with sensors that will gather continuous images of galaxies in the ultraviolet to study their shape, brightness and size. Ultraviolet light — the type of invisible energy that gives us a nasty sunburn — is at the higher end of the electromagnetic

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Notes From the Chair

Thomas A. Tombrello, Jr.

This is the sixth of these newsletters to our alumni and friends. Again we have included a few of the year's highlights. New faculty members in the Division are: Hee Oh, Associate Professor of Mathematics, who works in ergodic geometry; Nathan Dunfield, Associate Professor of Mathematics, whose research is in 3–dimensional topology and geometry; Re'em Sari, an Associate Professor of Theoretical Astrophysics and Planetary Science, who has been working on gamma ray bursters and the evolution of the orbits of extra–solar planets, and Sunil Golwala, Assistant Professor of Physics, who works in sub–millimeter astronomy and searches for dark matter. Steve Quake has become a Professor of Applied Physics and Physics, a joint appointment with the Division of Engineering and Applied Science, which strengthens our programs in nanotechnology and biophysics.

We, and the University of California have received substantial funding from the Gordon and Betty Moore Foundation to begin the design process for the California Extremely Large Telescope (CELT)/Thirty Meter Telescope (TMT). Our other partners in this effort are: NOAO/AURA and AURA's Canadian equivalent, ACURA. These partners are also actively seeking funding. The project office for the design study will be at Caltech's Center for Innovative Technology $(CIT)^2$, which in its previous incarnation was the St. Luke Hospital.

Two space missions, SIRTF and GALEX, that have substantial Division participation have been launched successfully and are returning extraordinary data. A brief report on GALEX is included in this issue. ◆

Inside

HONORS & AWARDS

Barry Barish
Nominated to serve as a member of the National Science Board; Elected fellow of the American Association for the Advancement of Science (AAAS); Hirommi Umezawa Distinguished Visitor at the University of Alberta, Canada

Pavel Batrachenko
Won gold medal at the 34th International Physics Olympiad in Taiwan

Danny Calegari
Awarded an Alfred P. Sloan Research Fellowship for 2003

Richard Ellis
Elected a Fellow of the American Association for the Advancement of Science

Alexander Kechris
Received the 2003 Karp Prize which he shares with Greg Hjorth (UCLA); chosen to give the 2004 Alfred Tarski Lecture at UC, Berkeley

Shri Kulkarni
Elected a Member of the National Academy of Sciences

Andrew Lange
Chosen to be 2003 California Scientist of the Year along with Saul Perlmutter

Lee Lindblom
Elected a Fellow of the American Physical Society

The Wide-Area Infrared Survey Explorer (WISE)

George Helou

Sky surveys have always moved astronomy forward in leaps and bounds, especially when the spectral domain is new and unexplored, or the gain in sensitivity or in solid angle is substantial. Caltech has led or been involved in a large fraction of the break-through surveys, starting with the Palomar Sky Survey, the Two-Micron Sky Survey (TMSS, Neugebauer and Leighton, 1968), the 12-to-100 micron IRAS survey (Neugebauer et al, 1983), and most recently the 2-Micron All-Sky Survey (2MASS), released in March 2003. TMSS and IRAS in particular were truly revolutionary. TMSS brought forth a population of infrared-bright stars, and demonstrated the crucial role of dust in the energy balance of the Milky Way. IRAS revealed infrared-luminous galaxies whose infrared radiation accounts for more than 90% of their total power output, stars with infrared excess emission indicating dusty disks and promising planetary systems like our own, and infrared cirrus, the extended wispy emission in the Milky Way whose spectral signature suggests Polycyclic Aromatic Hydrocarbons. 2MASS allowed us to bypass the dust extinction and map out in detail the stellar distribution in our galaxy, revealing a new class of brown dwarf stars, and uncovering at least a couple of dwarf galaxies in the process of being absorbed into the Milky Way. In addition to such remarkable discoveries, sky surveys yield uniform reliable data sets which are used to derive an unbiased, balanced characterization of classes of objects, and to find prototypes of rare, new objects.

WISE is the next generation infrared all-sky survey, a space-based mid-size explorer mission funded by NASA, with a goal of a thousand-fold improvement in sensitivity over IRAS. WISE will image the sky in four bands centered at 3.5, 4.6, 12 and 23 microns, with a spatial resolution in the 5 to 10 arcsecond range. Extrapolating from the known source populations, WISE is expected to find the most luminous galaxies in the Universe, find the closest stars to the Sun, and detect most main belt asteroids larger than 3km. Given its large step in sensitivity, WISE is certain to discover new phenomena in a broad range of contexts from the Solar Neighborhood to the Early Universe. It will also provide the data for a wide variety of systematic studies from the evolution of circumstellar debris disks to the history of star formation in normal galaxies.

In the meanwhile, the Spitzer Space Telescope, launched on 25 August 2003, started its very successful science mission on 1 December. It is quite different in design and capabilities from WISE: a larger aperture telescope, cooled with liquid helium and carrying a greater variety of instruments including spectrometers. Spitzer is an observatory, and will be devoted to more focused studies of specific regions and objects. While it can survey at comparable or deeper sensitivity than WISE, it can cover at most a few percent of the sky during its lifetime, and thus could not yield the uniform and comprehensive census of the Universe offered by WISE.

WISE will be a 50-cm telescope in a two-stage solid-hydrogen cryostat to cool detectors and optics; the cryogenic lifetime is anticipated to be six months for the survey mission, with additional time for check-out and a generous margin. The detectors are HgCdTe and Si:As arrays with 1024x1024 pixels, imaged to 2.2 arcsecond per pixel. This payload is mounted on a spacecraft placed in a 500-km circular, Sun-synchronous, polar orbit like the one used by IRAS. The telescope points essentially away from Earth, scanning the sky in repeating swaths as it goes around its orbit, until it achieves complete coverage of the sky. A scan mirror is used to compensate this scanning motion by keeping the sky image stationary on the arrays for a few seconds, then flying back to freeze the image of the next patch of sky on the array for a few seconds. This same technique was used on 2MASS and is being used on Spitzer successfully.

WISE was selected for an extended study phase by NASA after a highly competitive process, and will move upon successful conclusion of the current study into the development phase in late 2004, for a launch in 2008. The WISE Principal Investigator is Ned Wright from UCLA, with Science Team members Andrew Blain, Roc Cutri, Tom Jarrett, Davy Kirkpatrick, Carol Lonsdale and Charles Steidel from Caltech. The mission is managed by JPL, and the data processing will be the responsibility of the Infrared Processing and Analysis Center (IPAC) at Caltech.◆

Cosmic Explosions

F.A. Harrison & S.R. Kulkarni

Over the past six years there has been a veritable explosion of results on cosmic explosions and Caltech astronomers have been at the forefront. The Palomar 60-inch telescope (P60), constructed in the seventies as a "finder" for the 200-inch, has been automated and will be pressed into a focussed study of gamma-ray bursts (GRBs), the brightest cosmic explosions. P60 takes advantage of NASA's soon-to-be-launched Swift Explorer mission, which will survey the heavens for cosmic explosions.

Caltech astrophysicist, Fritz Zwicky, pioneered the study of cosmic explosions. Zwicky and Carnegie Observatory astronomer Walter Baade suggested that massive stars die explosively causing supernovae and leaving a residual compact object, a neutron star.

Astronomers now believe that even more massive stars may be expected to leave a black hole residue and some of these black holes power the brilliant GRBs. GRBs may well be sources bright TeV photons, be attractive targets for neutrino telescopes and LIGO. The brilliance of GRBs are also expected to serve as cosmic lighthouses and enable astronomers to study the young Universe. Clearly, GRBs are attractive targets to both astronomers and Physicists.

The Swift mission (launch, June 2004) is expected to localize one GRB a day! Profs. Harrison and Kulkarni spearheaded an effort to automate P60 and thus take advantage of Swift. P60 will respond rapidly to Swift events. Automated software pipelines will rapidly classify whether a GRB event is particularly interesting (i.e. coming from say redshift 6 or more) so that the astronomers can undertake detailed studies.

GRBs appear to be the tip of the iceberg of cosmic explosions. X-ray flashes (XRFs) are now recognized to be another class of cosmic explosions. P60 As one of the largest dedicated telescopes for GRB research, P60 is expected to provide a treasure trove of data for the astronomers.◆

BOOMERanG Redux: A First Baby Step Towards "Seeing" Inflation

Andrew Lange

The BOOMERANG experiment, which made headlines 3 years ago when it accurately determined the geometry of the universe, flew successfully over the Antarctic for a second time, in January of 2003.

BOOMERANG is a 1.2 m, balloon-borne telescope designed to study the Cosmic Microwave Background (CMB) from an altitude of 40 km above Antarctica. BOOMERANG provides an ideal platform for deploying state-of-the-art detectors developed at JPL by Principal Scientist Jamie Bock in collaboration with Goldberger Professor of Physics Andrew Lange.

During the first flight, the experiment used novel "spider-web" bolometric detectors to produce the first resolved images of the faint (~100 microK) intensity variations in the CMB. Analysis of these images showed that the geometry of the universe is flat and that the amplitude of structure in the universe is scale-independent, confirming two key predictions of the Inflationary Theory of the origin of the universe. This astonishing theory hypothesizes that the entire observable universe expanded at superluminal velocity some 10^{-32} after the Big Bang from a volume smaller than the nucleus of an atom.

The only direct relic of Inflation available for study today would be a cosmic background of gravitational radiation. Professor of Theoretical Physics, Marc Kamionkowski, and colleagues have recently shown that this gravity-wave background (GWB) might be detected via an extremely faint (< 100 nanoK) pattern imprinted in the polarization of the CMB. Detection of this signature would connect physics at sub-nuclear and cosmological scales and directly probe energies far greater than exist in any astrophysical setting or terrestrial laboratory. *(con't. on p. 9)*

HONORS & AWARDS

Michael Roukes
Granted a Norton Simon Research Foundation Award for his project Alliance for NanoSystems Biology

Anneila Sargent
Named the University of Edinburgh/ Royal Bank of Scotland Group Alumnus of the Year 2002;
Awarded the 2003 George Darwin Lectureship of the Royal Astronomical Society

Re'em Sari
Selected for this year's Mentoring Award by the Graduate Student Council

John Schwarz
Dannie Heineman Prize for Mathematical Physics for 2002 - the prize was awarded at the APS April 2002 meeting, Albuquerque, New Mexico

Chuck Steidel
MacArthur Fellow

Kip Thorne
Awarded the Robinson Prize in Cosmology from the University of Newcastle (United Kingdom);
Honorary degree from The Claremont Graduate University - Doctor of Humane Letters

Lisa Wang
Named to the First Team of USA TODAY's All-USA College Academic Team

Ahmed Zewail
Named a member of the Royal Swedish Academy

Bolocam

Sunil Golwala

Bolocam, a 144-element bolometer camera for observations at 1.1 mm and 2.1 mm at the Caltech Submillimeter Observatory, has largely finished its commissioning phase and is now available as a facility instrument at an introductory level. The instrument has been built by a collaboration consisting of James Bock (JPL), Jason Glenn (University of Colorado), Sunil Golwala (Caltech), Andrew Lange (Caltech), and Phil Mauskopf (Cardiff), with strong early support from Jonas Zmuidzinas (Caltech). Bolocam provides unique new capabilities for a variety of science topics, including surveys for dusty extragalactic submillimeter sources, surveys of protostars and thermal emission from other dusty sources in our galaxy, observations of the Sunyaev-Zeldovich (SZ) effect in known clusters, and blind SZ effect surveys for galaxy clusters.

Large surveys for dust-obscured galaxies have only become possible in recent years, thanks to the development of large-format bolometer cameras for operation at approximately 1 mm wavelength. Surveys performed over the last few years with the SCUBA (on the James Clerk Maxwell Telescope on Mauna Kea) and MAMBO (on the IRAM 30-m telescope at Pico Veleta in southern Spain) cameras have discovered a new class of galaxies, undergoing bursts of extreme star formation but containing so much dust as to be almost invisible in optical light. Most of the optical and UV photons emitted by the young stars in such galaxies are apparently absorbed by the large quantities of dust and reemitted at wavelengths longward of 100 μm. This reprocessed light is seen as a uniformly distributed background in the far infrared, detected by the FIRAS instrument on the COBE satellite. Some of the pioneering searches for these sources were performed by Caltech's Andrew Blain and collaborators, measuring the faint end of the luminosity function (number density as a function of flux) and finding counterparts at radio wavelengths. David Frayer at the Spitzer Science Center and collaborators used the interferometric array at Caltech's Owens Valley Radio Observatory to make one of the first identifications of CO emission from such sources and thereby solidly establish the redshift and begin to provide information about the physics of such sources. More recently, Blain and Scott Chapman at the Spitzer Science Center have found optical identifications and redshifts for a large number of such sources using the Keck telescopes and thereby determined their redshift distribution. The density of such sources peaks at a redshift of about 2, which coincides with the peak in star formation seen at UV and optical wavelengths via the existence of the Lyman-break galaxy population first discovered by Caltech's Chuck Steidel.

Bolocam promises to make a significant contribution to this field by mapping larger areas than have been done before. This is possible because of the excellent quality of the site and the sensitivity and stability of the bolometric detectors; Bolocam can operate in ways not previously possible for bolometric cameras on large telescopes, including fast scanning modes that obviate chopping and its resulting observing inefficiency. Such large surveys will enable precise measurement of the bright end of the luminosity function and also, hopefully, the clustering properties of these galaxies, both with each other and with sources observed at other wavelengths. These additional pieces of information should allow significant refinement of our understanding of how these unusually luminous but until recently unknown sources relate to the larger cosmic web of dark matter and galaxies. Bolocam's first such survey was performed in January and May, 2003. It was a narrow, deep survey, intended to measure the confusion limit for this particular combination of angular resolution and wavelength. (At sufficiently low fluxes, the number of sources per angular resolution element becomes so large that it becomes impossible to resolve them; this is termed "confusion" and the flux at which this occurs is the "confusion limit.") Analysis of these data is currently in progress, but we are fairly confident that sources have been seen. A publication on the luminosity function of the observed sources is in preparation. Spring 2004 will likely see a wide, shallow survey that will provide the first good constraints on the high end of the luminosity distribution of these FIR/submm/mm-wave sources. The coming years will hopefully see significant overlap between fields observed by Bolocam, SIRTF, and other FIR/submm/mm-wave instruments, as well as observations at optical/IR and radio wavelengths, providing a full picture of the thermal emission from these fascinating objects.

One of the other primary goals of Bolocam is to find the coldest protostellar condensations in the galaxy. By operating at 1 mm, Bolocam is capable of seeing cores as cold as 10-20 K. Simple discovery and study of such sources, followed by a precise census of such sources as a function of their temperature, will provide input to models of star formation in normal galaxies like ours. The galactic surveys for protostellar sources have been done in collaboration with the SIRTF Legacy Cores to Disks team, led by Neal Evans (University of Texas) and with participation by Anneila Sargent (Caltech) and graduate students at each of these institutions. New sources have been discovered, and Caltech astronomy graduate student Melissa Enoch has done followup observations with the CSO's SHARCII 350 μm camera to determine the temperatures of these sources. Publications on the galactic work are in preparation.

Recently completed (November, 2003) is a survey at 2.1 mm for galaxy clusters using the Sunyaev-Zeldovich (SZ) effect. Galaxy clusters are some of the most extreme objects in the universe, having formed from the most significant excursions in the density fluctuation field present in the universe since very early times (such fluctuations are thought to have originated from quantum fluctuations of a putative inflationary scalar field). Their abundance is thus very sensitive to parameters that affect the number and growth of such density fluctuations, such as the density of matter, of dark energy, and possible evolution in the physical parameters of dark energy.

The SZ effect consists of the Compton up-scattering of cosmic microwave background photons by the hot electrons in galaxy clusters. Being so large and massive, the virial kinetic energy in clusters is large and thus the gas in such clusters

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Cosmic Background Imager Probes Dark Matter and Dark Energy

Anthony Readhead

The oldest radiation in the universe decoupled from matter just 400,000 years after the Big Bang and survives as an ancient fossil in the cosmic microwave background. This fossil provides an accurate picture of the state of the universe at the decoupling epoch and is a cosmologist's dream, since the structure in the universe at this early epoch consisted simply of tiny fluctuations in the density of the matter (and radiation), which, under the influence of gravity, eventually gave rise to all the remarkable range of structures that we see around us today – from clusters of galaxies to galaxies, stars and planets. Following the decoupling epoch, just 400,000 after the Big Bang, came the "Dark Ages" of astronomy – a period of one billion years during which the seeds of galaxies and clusters that can be seen in the fossil radiation (Figure 1) grew to produce galaxies and stars and hence the light used so effectively by optical astronomers to trace the evolution of the universe from an age of 1 billion years to the present age of 13.8 billion years. To grasp the relative timescales shrink these by a factor of one billion and the fossil radiation originates 3.5 hours after the Big Bang while the Dark Ages last 1 year. The density fluctuations at the decoupling epoch are so small that the physics governing their behavior is simple and therefore easy to interpret. Given that it took about 1 billion years for the first galaxies to grow from the seeds present at decoupling it is a simple matter to calculate the magnitude of density fluctuations that were present at decoupling and hence the expected temperature fluctuations in the fossil radiation. By 1989, using the 40m telescope at Caltech's Owens Valley Radio Observatory, we had shown that the temperature fluctuations were far smaller than predicted, proving definitively that most of the matter in the universe was "dark matter", and not only dark, but also of an exotic nature which interacted much more weakly with radiation than ordinary matter.

Advances in receiver technology led to a new generation of instruments that were one hundred times faster, a prime example being Caltech's "Cosmic Background Imager", shown in Figure 1, sited at an altitude of 16,800 feet in the Chilean

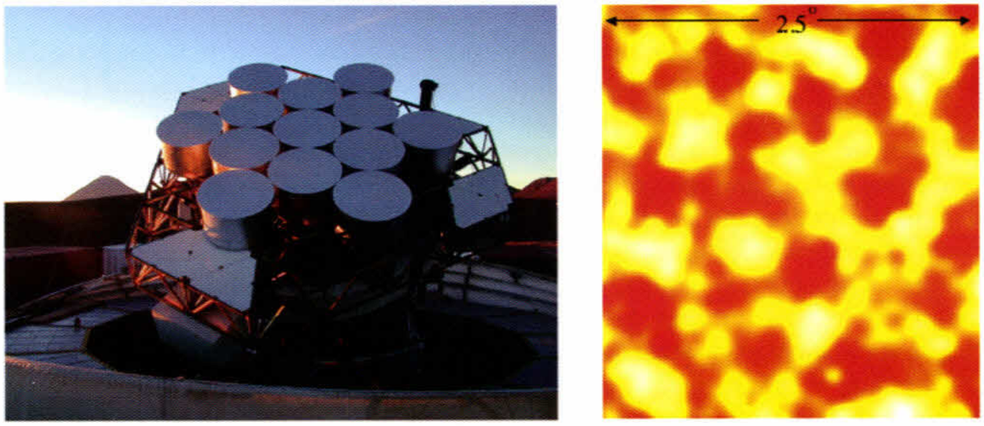

Figure 1: The "Cosmic Background Imager" (CBI) is a 13-element radio interferometer operating at 16,800 feet altitude in the Chilean Andes. This instrument was the first to make images of the seeds that gave rise to clusters of galaxies (right). These seeds are seen as tiny temperature fluctuations of about ten millionths of a degree in the fossil radiation left over from the Big Bang. Hotter regions indicate higher densities of "Dark Matter".

Andes. The CBI was supported by generous donations from Ronald and Maxine Linde, and from Cecil and Sally Drinkward, and from other private Caltech funding and the National Science Foundation. The CBI provided the first images of the seeds that gave rise to clusters of galaxies, and also the first evidence of a predicted drop in the level of fluctuations on small angular scales, confirming a pillar of cosmological theory. Also, in agreement with a number of experiments at larger angular scales, notably the Boomerang experiment led by Andrew Lange, the CBI provided independent evidence drawn from smaller angular scales that the geometry of the universe is flat in the sense that parallel lines never converge or diverge, and that the dominant energy constituent in the universe is "Dark Energy".

As a result of these observational developments, and of parallel developments in optical astronomy, the "standard" cosmological theory is now based on dark matter and dark energy. While the theory does an excellent job of reproducing the angular spectrum of the temperature fluctuations in the fossil radiation, it is based on complete ignorance of the nature of the dark matter and the dark energy. Physics has no explanation for these components, and it is clear that fundamental changes in physics are needed to explain these, the major constituents of matter and energy in the universe. The focus has now shifted to observations of fluctuations in the polarization of the fossil

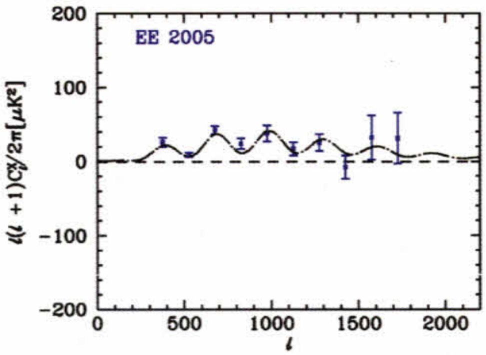

Figure 2: Expected level of sensitivity to fluctuations in the polarized fossil radiation that should be achieved by the CBI by 2005. The black curve shows the theoretical prediction based on the best-fit cosmological model to the total intensity fluctuations. Deviations from the theory could cast light on the dark matter and dark energy which dominate the matter and energy of the universe.

radiation in the hope that this might provide clues to the nature of dark matter and dark energy. The CBI was therefore upgraded to polarization capability with a generous donation from Fred Kavli, and reconfigured for these observations. The reconfigured, upgraded instrument is shown in Figure 1. The instrument has now been operating in this mode for one year and the first 100 nights of data have been analyzed. These show that the CBI is achieving the expected level of sensitivity, that the known sources of contamination are being successfully eliminated, and that there therefore appear to be no obstacles to measuring the extremely faint levels of polarization predicted. When the remaining observations are analyzed we can

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Understanding the Dark Side of the Universe with SNAP

Richard Ellis

These are exciting times in observational cosmology. Scarcely a month goes by without press coverage of another triumphant experimental result that indicates we live in a puzzling Universe containing material and energy sources we don't really understand at all. Caltech's famous Fritz Zwicky left us with the legacy of *dark matter.* Inferred originally via the motions of galaxies and later through the elegant applications of gravitational lensing (the bending of light by mass as predicted by General Relativity), the evidence that only a fraction (15%) of the gravitating matter in the cosmos is baryonic is now widely agreed but the nature of the remaining matter remains a mystery. In 1999, two teams of astronomers found distant supernovae are systematically fainter (and hence further away) for a given redshift than expected if the cosmic expansion was slowing down by its own gravity. A mysterious *dark energy* has become the fashionable explanation for the cosmic acceleration inferred from the supernovae data. It seems this dark energy may be the dominant term in governing the present cosmic expansion, suggesting the Universe will expand indefinitely. However, this interplay between the attractive force of gravity and the repulsive effect of dark energy might have been very different in the past. 6-7 billion years ago, dark matter might have had the upper hand. At that time gravity played a key role in the assembly of structures like our own Milky Way galaxy. Understanding this time-dependent contest between dark energy and dark matter is one of the hottest topics in astronomy whose outcome will surely have major implications for fundamental physics.

The term "precision cosmology" is frequently used in recent popular scientific articles. Many of the components of the cosmos and their properties are now claimed to 10% accuracy - a precision may seem derisory to the laboratory physicist but one that represents real progress compared to 15 years ago when there were no stringent observational constraints in cosmology at all. But don't confuse *measurement* with *understanding*; we have a long way to go yet and doubtless there are many surprises in store. A key question is exactly how the dark energy manifests itself. Is it a constant term analogous to that originally introduced by Einstein? Or does it represent the negative pressure of a scalar density field which can take a wider set of possibilities, conceivably varying with time in a manner somehow connected with the evolving mass density? To constrain the possibilities, observations are needed that directly address the interplay between dark matter and dark energy through their effect on the cosmic expansion history and the rate of structure formation. Studying the time-dependence of these phenomena is the key to making progress and this is why new observations, in addition to those offered by pioneering studies of the microwave background, are necessary.

The Supernova/Acceleration Probe (SNAP) is a proposed space telescope which would be dedicated to addressing the time-dependent aspects of dark matter and dark energy. The unique feature of SNAP is its panoramic field of view. Whereas Hubble Space Telescope has optical CCD and infrared imaging cameras with fields of 1-4 arcmin, SNAP comes equipped with a focal plane which spans a spectacular 0.7 degrees across. This wide field (Figure 1) ensures a huge advantage in surveying the deep Universe for signs of the battle between dark matter and dark energy.

Figure 1: SNAP, the Supernova Acceleration Probe, is a proposed wide field 2m space telescope equipped with a large mosaic of optical and infrared detectors. By slewing across the sky, multicolor imaging to depths equivalent to the deepest Hubble images will be obtained over hundreds of square degrees enabling precision studies of over 2000 distant supernovae and the weak distortions of millions of background galaxies induced by the distribution of dark matter viewed at various cosmic times.

SNAP has two broad goals. Its wide field enables it to detect very faint supernovae in abundance and with great photometric precision. During a 2 year period dedicated to the primary purpose of the mission, over 2000 high quality measurements of distant supernovae would directly track the rate of expansion over the past 70% of cosmic history. The second application utilizes the weak distortion in the shapes of background galaxies induced by the gravitational lensing effect of foreground mass. By examining this signal in different redshift slices, a direct measure of how structure grows can be made. Both the supernovae and weak lensing measures give equally precise constraints on dark energy but using completely different physical probes (Figure 2).

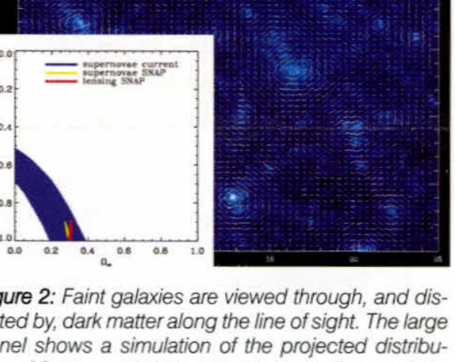

Figure 2: Faint galaxies are viewed through, and distorted by, dark matter along the line of sight. The large panel shows a simulation of the projected distribution of foreground dark matter in a small area of sky and its effect on the orientations of faint background galaxies (vectors). By slicing the background galaxies according to their distance utilizing multicolor information, constraints on the dark energy index, w (inferred through time-dependent growth in the clustering of dark matter) will complement those from studying distant supernovae (inset).

Caltech is a charter member of the SNAP team (which involves several institutions led by DoE-funded Lawrence Berkeley Laboratory) and coordinates the weak lensing component of the science case for SNAP. Jason Rhodes (Caltech) heads an international working group which has developed simulation tools, based on actual Hubble images, which predict how precisely SNAP is likely to recover lensing signals. These tools have formed a crucial aspect in the optimal design of the mission.

In addition to Caltech's central role in a key component of the SNAP science, Caltech and JPL are also involved in

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Finding the Best Site for the World's Greatest Telescope

S. George Djorgovski

"More light!" was the rallying cry of George Ellery Hale, the founding father of Caltech, Mt. Wilson and Mt. Palomar observatories, and much else besides. Today, Hale's vision is still very much alive, as Caltech and several collaborating institutions are developing a design for a next-generation telescope, a 30-m diameter successor to the Kecks, with a collecting area an order of magnitude larger. This giant telescope, known locally as CELT (for California Extremely Large Telescope), and more recently as the TMT (the Thirty Meter Telescope) is now a joint venture of Caltech, the University of California, the Association of Universities for Research in Astronomy (AURA), which operates most of the U.S. national observatories, and its Canadian counterpart (ACURA; no, they do not make cars). With its light gathering power, a sharp vision from Adaptive Optics (AO), and revolutionary instruments, this Giant Optical Device will revolutionize astronomy of the early 21[st] century.

But where do you build such unique facility? The world's greatest (and most expensive) telescope should be placed at the best possible site. The choice of a site affects directly the resulting science, both in the amount (through the number of clear nights) and the quality (through the level of atmospheric turbulence, or "seeing"). It also affects the design of the telescope (wind loads, seismicity), the cost of the construction and operations, and the mode of operation (How remote is it? Is there enough oxygen to breathe? Is there a Radio Shack nearby? And so on.). Site selection is very much a critical path item for the CELT/TMT.

As it turns out, the art and science of astronomical sites is not as well developed as one may wish. In the past, many great observatories were built within an easy driving distance of some university campus or at least a sizable town where the staff would be willing to live. We are now much more interested in sites which are high, dry, and very boring – the presence of oxygen, water, and pretty landscape tends to attract humans, which then generate light pollution. The choices in the past were largely based on the seeing-limited visible-light observations, whereas now we care a lot more about the AO and infrared wavelengths. All too often, it would also depend on the influence of the local Senator. Large, objective, uniform, modern data sets which can be used to evaluate and compare possible high-quality sites simply do not exist.

We have thus embarked on an ambitious site testing and evaluation program for CELT/TMT, with a goal of gathering large quantities of homogeneous, high-quality data for a number of possible sites, which can then inform a site decision. This is by far the best astronomical site-testing program ever done (unfortunately, that is not saying much), with an interestingly multidisciplinary character: from climatology and geology, to atmospheric turbulence theory and experiment. This has been a joint effort by Caltech and AURA, with an increasing participation expected from our UC and ACURA partners. The Caltech team is led by the author, and it includes Dr. Matthias Schoeck, an SRF in Astronomy, and Dr. Warren Skidmore, a Postdoctoral Scholar. The AURA team is led by Dr. Alistair Walker, now a Director of the Cerro Tololo Interamerican Observatory (CTIO) in La Serena, Chile.

The general belief is that the best astronomical sites are either isolated high mountains in temperate oceans (e.g., Mauna Kea and La Palma), or coastal mountain ranges near a cold ocean with stable subtropical anti-cyclone conditions (e.g., coasts of Chile, California/Baja, and Namibia). Exceptions may exist; for example, there is an apparently good continental site in Uzbekistan (Maidanak), but for obvious the reasons it would not be practical for us. Neither is Antarctica, which is very dry, and is a good place for specialized CMBR experiments. While other as-yet undiscovered good sites may exist, given our short time scale (a site decision in about 3 or 4 years from now), we decided to focus our efforts on Mauna Kea (MK), northern Chile, and W/SW USA and northern Mexico (La Palma is not known to be better than MK, and Namibia seems to be worse than Chile, in addition to the logistical problems).

Probably the most difficult problem is posed by the nature of the Earth's atmosphere: it is a highly complex system (both in the figurative and technical sense of the term), and nearly every measured quantity (e.g., the mean temperature, or atmospheric turbulence) is behaving as a *1/f* noise. Thus, long time baselines are necessary, but even they do not guarantee that the best site today will still be the best in 10 or 20 years. In fact, we are statistically almost guaranteed to pick local minima and be sorry later, but we will try to minimize such biases by leveraging all long-term data available to us.

We began with studies of the cloud cover and precipitable water vapor (PWV) using homogeneous satellite data. The PWV is of little importance for wavelengths shorter than about 2 microns, but is detrimental for mid-IR observing. These data sets cover large areas of the world, uniformly, and over time baselines of several decades (this is essential, in order to place the measurements in a long-term climatological context, and take out the cyclical variations such as El Nino). The interpretation of the satellite imagery requires a specialized knowledge, so these studies were done by Dr. Andre Erasmus, a consulting astro-meteorologist. The results were sometimes unflattering to some of the existing observatories, but they gave us an objective way to select short lists of candidate sites to be considered further. The very best sites have clear fractions close to 80%. We also use some basic geographical criteria, e.g., the highest, isolated mountains away from big cities or other sources of light pollution (in Chile, these include large open-pit copper mines, which can generate amounts of light comparable to a mid-sized city). The most promising sites are then selected for seeing measurement campaigns, which must be done on the ground.

In the North America, the clearest skies are in the southern California (Hale chose well) and northern Baja, whereas a number of interesting mountains can be picked in California, all of them are politically unattainable, being in the National parks or similar protected areas. The only viable site, and perhaps the best one in the continental North America, is San Pedro Martir in the northern Baja California, where the Mexican National Observatory

(continued on page 8)

Telescope *(from page 7)*

is situated (they have chosen well, too). We are working with our Mexican colleagues on a more detailed characterization of this site.

In the northern Chile, there is a dichotomy between ~ 2 – 3 km high coastal mountains which have very high clear fractions, but also a high PWV, and ~ 5 – 6 km high mountains in the Altiplano area, which are cloudier, but have a low PWV. An example of the former is Cerro Paranal, where the European Southern Observatory has built their Very Large Telescope (VLT) facility, a set of four 8-m telescopes and several smaller instruments. An example of the later is the Chajnantor area, where Caltech's Cosmic Background Imager (CBI) telescope is situated, and where the next-generation international mm radio telescope array, ALMA, is being built. Our plan is to test at least two new sites of either type.

The seeing, usually parameterized as a full-width at a half-maximum (FWHM) of a stellar image point-spread function (PSF), is probably the single most important parameter for an astronomical site. The signal-to-noise of most measurements is inversely proportional to the area of the seeing disk; i.e., the seeing diameter is as important as the telescope diameter! On a more detailed level, the atmospheric turbulence is parameterized by a number of parameters, all of which affect the design of the AO systems. However, as a rule, the effectiveness of AO is strongly correlated with the seeing – it simply makes a good seeing better – and it cannot be used as a cure for a bad seeing.

In order to characterize a site properly, seeing measurements and other data should be collected over a long period, spanning at least one full annual cycle, in order to average over the seasonal variations and inevitable fluctuations in the weather. Such measurements are being gathered at many existing observatories, but our task is to provide them for a set of remote sites with no infrastructure or human presence. Thus, we have designed a robotic observatory for atmospheric characterization of potential telescope sites. The equipment has to be robust and reliable, operating in a highly automated fashion, unattended, over periods of months or longer. It has to be portable by 4WD trucks and erected without major construction equipment. We include a satellite internet connection and webcams, for remote operation, testing, and problem solving when needed, and a battery-backed solar power system. We will deploy up to 6 or 7 such mini-observatories at various remote sites over the next couple of years. The first one has been installed at a Chilean site in October 2003, and is now gathering the data. It is currently the smallest astronomical observatory operated by Caltech – other than the rooftop telescopes atop of the Robinson Lab!

The centerpiece of these site-testing observatories is a robotic 30-cm telescope on an elevated platform, equipped with a dual instrument, a combination of a Differential Image Motion Monitor (DIMM) and a Multi-Aperture Scintillation Sensor (MASS). The former is now standard instrument for measurements of astronomical seeing, including the atmospheric turbulence parameter r_0, where we made some minor technical innovations. The other is a novel type of instrument, developed by Dr. Andrei Tokovinin (now at CTIO), and it produces measurements of the "free atmosphere" seeing (i.e., excluding the turbulent ground layers), values of several turbulence parameters, and even rough vertical profiles of the atmospheric turbulence (the C_n^2 structure parameter). These instruments may be supplemented by a set of microthermal sensors on a 30-m mast, which would measure the temperature profiles of the lowest layers of the atmosphere (the temperature gradients are closely related to the turbulence), and possibly also a SODAR, an acoustic sounder (essentially a sonar with the signal bouncing from the density inhomogeneities in the lower atmosphere). A fully automated meteorological station completes the equipment set; we are especially interested in the distribution of wind speeds and directions, and the possible correlations of the various meteorological parameters with the seeing. Some additional instruments are also being considered.

Our plan is to deploy several of such testing stations in parallel, in order to provide a fair comparison of the various sites. We will also supplement the ground-based measurements with the contemporaneous satellite data (thus placing them in a long-term climatological context; we want to know if we have an unusual year). Finally, we are also producing computational fluid dynamics (CFD) simulations of the airflow and the resulting turbulence over the sites, over a range of the measured wind speeds and directions. Such simulations can help us understand better the data and the trends we will be measuring.

A perceptive reader has noticed that all of the sites we are considering are in the geologically highly active areas, and indeed all of them are colored uniform red on the earthquake hazard maps. Broadly speaking, the earthquake danger in the northern Chile is comparable to that in Pasadena. This is a concern, but not an insurmountable problem: we know how to build to the code. We will be acquiring geological studies for every site under consideration.

At the end of an approximately 3-year period, we will have an unprecedented data set on some of the potentially best telescope sites in the world. This will help us decide where to build, but it will also represent a legacy for the future telescope projects. At the chosen site, the effort will morph into a detailed atmospheric characterization, which will help optimize the AO design and other aspects of the project.

While these data will be essential in judging which sites hold most promise for the scientific requirements of the observatory, a number of other practical, logistical, and political issues must be considered. Some sites may not be obtainable for political or cultural reasons. Some may be so remote or inhospitable to make the construction and operation of such a high-tech facility and the necessary infrastructure (roads, emergency services, etc.) prohibitively expensive. Some sites may be attractive because of an existing infrastructure or a proximity to other facilities. Some may be in politically or economically unstable areas, and the physical safety of the people and the facility may be an issue. In some cases it may be hard to recruit and retain the necessary qualified staff. Prospects for a local economical growth can make some of the challenges easier, but also bring the possibility of an increased light pollution. And so on, in a very complex problem which combines strands of science, engineering, management, sociology, and politics – but with a crystal-clear aim of optimizing the long-term scientific returns from the greatest new telescope in the world.◆

BOOMERanG *(from page 3)*

Motivated by this possibility, Caltech graduate student Bill Jones, working with Bock and Lange, developed a new type of bolometric detector that is capable of measuring the polarization of the CMB with high sensitivity. These detectors were successfully integrated into BOOMERANG during summer 2002, just in time for the January 2003 flight. The images produced during the flight cover 100 square degrees of the sky with 10' angular resolution and high sensitivity to CMB polarization. They complement in angular resolution and sky coverage the data being gathered by Rawn Professor of Astronomy, Tony Readhead's, Cosmic Background Imager (CBI) in Chile. BOOMERANG and CBI should together provide the first detailed picture of the polarization of the CMB, which was first detected just one year ago by the DASI experiment at the South Pole.

Detecting the extremely faint imprint of Inflation in the polarization will require a new generation of more powerful experiments. Three new experiments which use the polarized bolometers pioneered on BOOMERANG are currently being deployed to the ends of the Earth and beyond: two new telescopes (BICEP and QUAD) will be sited at the South Pole in 2005; a satellite (Planck) is scheduled to be launched in 2007 into an orbit ~ 1 million miles from Earth, around the second Lagrangian point of the Earth-Sun system. These experiments might detect the polarization signature of Inflation, but only if Inflation occurred at the very high end of the theoretically favored range of energies.

A definitive search for the polarization signature of Inflation will require a future orbital mission optimized specifically for this task. So compelling is this goal that NASA has inserted such a mission in its "Beyond Einstein" program and already funded three concept studies. Bock at JPL is leading a study team that includes scientists from Caltech, Chicago, JPL, NIST, Stanford, UC Berkeley, UC Davis, and UC San Diego, as well as international collaborators. The mission concept that has emerged - Experimental Probe of Inflationary Cosmology (EPIC) would use a radically new detector concept now being developed in a JPL-Caltech collaboration that includes Bock, Lange, JPL Scientists Rick LeDuc and Peter Day, and Caltech Professors of Physics Jonas Zmuidzinas and Sunil Golwala. The new concept is a marriage between the highly sensitive bolometers developed by Bock and Lange and the sophisticated superconducting antenna structures developed by LeDuc and Zmuidzinas for sub-mm heterodyne applications. More information on these efforts can be found at http://www.astro.caltech.edu/~lgg/. ◆

Galaxy *(from page 1)*

spectrum, just above visible light in frequency, but below X-rays and gamma rays.

A device called a spectrometer will break down the light into its component colors, just as a prism separates white light into a rainbow. These measurements will enable scientists to determine the distances of galaxies — and thus, their places in cosmic history — and the rate at which stars are forming within those galaxies.

Telescopes are like time machines. Because of the finite speed of light, we see galaxies as they appeared in the distant past. Light traveling from a galaxy 1 million light-years away requires a million years to reach us, and so we see the galaxy as it appeared a million years ago. By observing many galaxies at varying distances from us, the mission will construct a history of how galaxies evolved through 80 percent of the age of the universe.

"This mission is providing the first comprehensive map of a universe of galaxies under construction and is bringing us closer to understanding how they, and our own Milky Way, were built," said the mission's principal investigator, Dr. Christopher Martin, an astrophysics professor at the California Institute of Technology in Pasadena.

Scientists will use data from the mission to learn when carbon, oxygen and the other chemical elements were created inside blazing stars. Most of the elements found in the human body originated in stars; we are literally made of stardust.

In addition, the mission will conduct the first ultraviolet surveys of the entire sky beyond our own galaxy, including the first wide-area spectroscopic surveys. Rich in objects from galaxies to quasars to white dwarf stars, this vast data archive will serve as a resource for the entire astronomical community.

The spacecraft's ultraviolet observations will complement NASA's Space Infrared Telescope Facility, launched August 26 of this year, and the James Webb Space Telescope, launching in 2010. The Galaxy Evolution Explorer will also help pave the way for future Hubble Space Telescope observations by identifying intriguing celestial objects for study.

As of November 19, 2003, GALEX has observed about 5% of the sky. The data have demonstrated that the instrument and satellite are performing as expected. Many spectacular ultraviolet images of galaxies have been produced. The science team has made many early discoveries and is currently working feverishly to convert these to science publications. Among these include the observation that galaxies are forming stars far outside their main bodies as traced by optical and infrared light (the light of old stars). These include galaxies in the process of growing larger, and new galaxies that may be formed during tidal encounters between existing galaxies. GALEX is actually observing galaxies evolving, and possibly even forming in the universe today. Using GALEX, evolutionary processes, many important in the distant universe, can be studied in detail nearby.

The Galaxy Evolution Explorer mission is led by the California Institute of Technology, which is also responsible for science operations and data analysis. NASA's Jet Propulsion Laboratory, Pasadena, Calif., a division of Caltech, manages the mission and built the science instrument. The mission was developed under NASA's Explorers program, managed by the Goddard Space Flight Center, Greenbelt, Md. Orbital Sciences Corp., Germantown, Md., is responsible for the spacecraft, integration and testing, launch vehicle, ground data system and mission operations. Other partners include the University of California, Berkeley; Yonsei University, Seoul, South Korea; Johns Hopkins University, Baltimore, Md., and its Space Telescope Science Institute; and the Space Astronomy Laboratory (Laboratoire Astronomie Spatial), Marseille, France.

More information about the mission is available on the project web site at: www.galex.caltech.edu ◆

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Bolocam *(from page 4)*

heats up to very high temperatures (10^8 K). Such gas of course emits in the X-ray by free-free scattering, but it also acts to "warm" the CMB passing through it via simple Compton scattering. The CMB is a remarkably uniform and well-understood backlight, so measurement of fluctuations in the CMB due to such clusters can give a fairly good measure of the cluster mass. In fact, a SZ-flux-limited survey is approximately mass-limited and thus can observe galaxy clusters out to their redshift of formation. Though other groups have performed similar blind surveys, Bolocam is the first instrument with the combination of sensitivity and angular resolution needed to find clusters in this unbiased fashion. Given the sensitivity of galaxy clusters to cosmological parameters, a survey with such a relatively simple selection function can be very informative. Bolocam will soon have a friendly competitor, the Sunyaev-Zeldovich Array, an interferometric array to be sited at the new high-altitude site for Caltech's Owens Valley Radio Observatory. Design and construction of the array has been led by John Carlstrom (University of Chicago) with significant contributions by OVRO scientists and staff.

As Bolocam becomes fully available as a facility instrument, there is no doubt that observers will conceive of new and unique projects. We look forward to a long, useful lifetime for the camera and for it to help maintain the CSO's leading stature in the field of submillimeter and mm-wave astronomy and cosmology. ◆

SNAP *(from page 6)*

technical studies. A major challenge is the space readiness of the large array of mosaic infrared detectors needed to ensure the multicolor aspects of the science program. Keith Taylor and Roger Smith at the Caltech Optical Observatories are working with JPL colleagues led by Chas Beichman to examine these questions, for example with colleagues at the Rockwell Science Center. Investment in frontier detector technology has the added benefit of immediate spinoffs for instrumentation on Caltech's ground-based telescopes.

Although SNAP is not yet a funded mission its 'stock' is rising rapidly. DoE and NASA recently announced their intent to finance a *Joint Dark Energy Mission* for which a wide-field space telescope like SNAP is viewed as the primary contender. The scientific community (and public) have been quick to realize that unraveling the cosmic mystery of dark matter and dark energy is one of the most important puzzles faced in fundamental physics. Both NASA and DoE are already funding design effort, both technically and in terms of science planning. Caltech astronomers are gearing up to exploit these new opportunities in a major way in the next few years. ◆

Cosmic *(from page 5)*

expect to detect the polarization fluctuations over a wide range of angular scales with the CBI, and the analysis of three years' observations should provide an accurate spectrum of these fluctuations enabling us to make a detailed comparison with the precise predictions of the theory based on the total intensity fluctuations.◆