SEU Roadmap II v3

7/2/02 draft

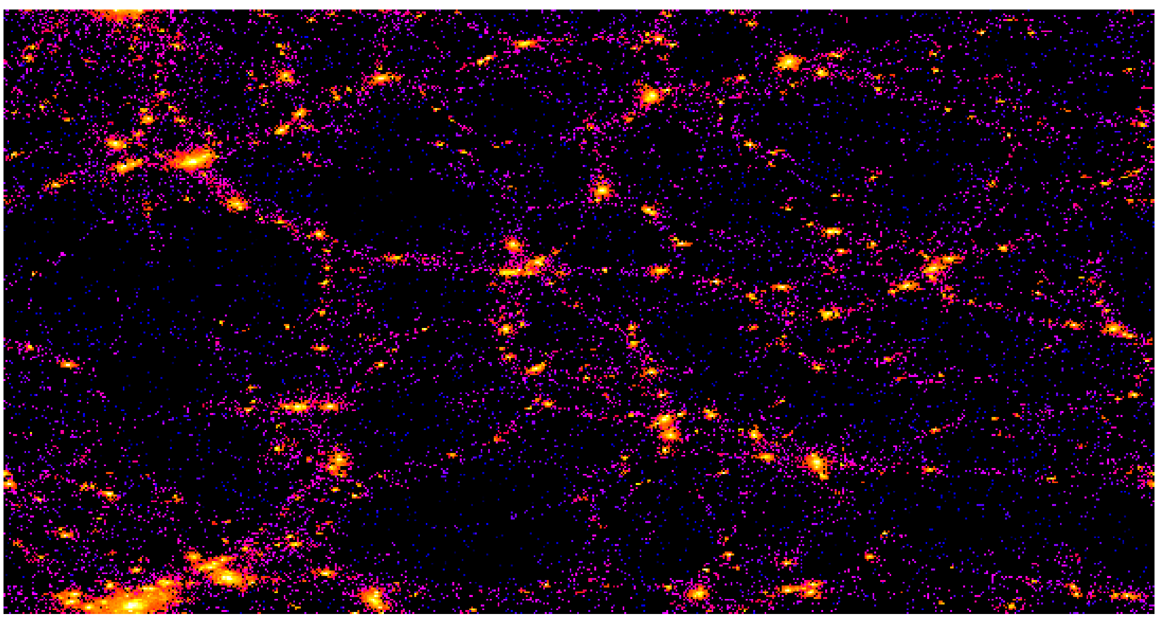
by D. Lester and the Roadmap II team

A Rich and Diverse Universe

Our efforts to understand the structure and evolution of the Universe are carried out on a broad front, with complementary clues to its origin and destiny coming from different wavelength regimes and astrophysical venues. The SEU theme views the Universe as a dynamic, evolving, and active place -- the cosmic manifestation of the web of biological and physical interactions that determine the future of our own planet.

This cosmic ecosystem is one of layered complexity. The Universe is organized out of cycles of matter and energy, a cosmic web of physical processes in which the chemical elements are formed and destroyed, and passed back and forth between stars and diffuse clouds. It is illuminated with the soft glow of nascent and quiescent stars, fierce irradiation from the most massive stars, and intense flashes of powerful photons from collapsed objects. Even as the Universe relentlessly expands, gravity pulls pockets of its constituents together, and the energy of their collapse and the resulting nucleosynthesis works to fling them back apart. We in the SEU theme seek to map out and understand this web of interrelationships and dependencies of the Universe. We want to know what powers it, and how that power is regulated and transmitted. This document gives a brief review of what we know, and focuses on our approach to the task.

A web of matter and connections …



As the web of primordial material condenses into the first galaxies, the interactions of light and matter constitute a similarly complex web of interdependence. It is such a picture of our cosmic ecosystem that the SEU theme is poised to explain.

While our Universe is a magnificent laboratory for studying processes of matter and energy that we cannot yet hope to duplicate on our Earth, it is a laboratory in which there are a lot of things going on simultaneously. Our understanding depends upon our ability to use new technologies and creative strategies to build the tools that can disentangle this cosmic web. With a nod to the best strategies of terrestrial archaeology, our perspective of exploration is based not only on the cycles of matter and energy that we can see operating right now, but on the fossil record of dead stars and their chemical constituents, which are the ashes that they leave behind.

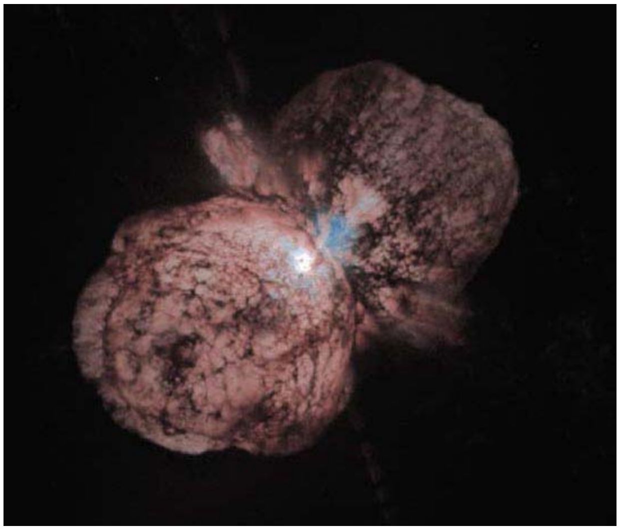
The spirit of exploration is at the foundation of our culture. Investment in this spirit has never failed to strengthen us and improve our quality of life. While our curiosity drives us to explore diverse frontiers -- oceans and continents, bacteria and the brain, the common thread is a desire to uncover the richness of the world in which we live, a richness that is inevitably valuable and transforming. Our efforts to date have revealed our Universe to be an awesomely rich and diverse place. By looking out at it we see things that we have never seen before. We see things that challenge both our understanding and our imagination, and we are to committed to bring this challenge to the whole country though our outreach efforts.

The intellectual challenge for the SEU theme encompasses the birth, death, lifecycles, and interrelationships between galaxies, stars, black holes, and the gas, dust and radiation fields that permeate the space between them.

Stars: Engines of Change in an Evolving Universe

Originating in dense gas clouds, which condense and fragment, stars are a critical part of the machinery of the evolving Universe. For a star, mass is destiny -- the low mass stars slowly fuse hydrogen into helium, while massive stars burn fiercely for a brief cosmic moment. Stars about one half the Sun's mass or less have a lifetime which is at least as long as the present age of the Universe: the oldest stars in the Milky Way Galaxy contain a sample of the Universe from some 12 billion years ago. These stars show that our Galaxy was once very poor in the heavy elements out of which planets and people are made. More recently formed stars, like the Sun, have inherited a legacy of atoms created in the massive stars that lived out their short life cycles when the Universe was young.

Massive stars make essentially all of the elements of our world—oxygen, calcium, iron—and they blast these new elements into the gas between the stars as they end their lives in supernova explosions. In these violent events a single dying star, as it undergoes a catastrophic collapse into a neutron star or black hole, shines as brightly as a billion Suns while accelerating cosmic rays, forming cosmic dust, and stirring the magnetic field between the stars. Such stars are the major source of energy for the interstellar medium. The accumulated products of all these complex events become the material for new stars which form from the densest regions of the interstellar gas. In these dusty and obscure venues, the atoms can combine into molecules, including organic molecules related to life. Understanding how these complex events are related, from nuclear reactions through the formation of stars and their planets, is a prerequisite to understanding the origin of life in the Universe.



From gas to stars and back again …

A huge, billowing pair of gas and dust clouds is captured in this stunning Hubble telescope picture of the super-massive star Eta Carinae, which is about 8000 light years away. Eta Carinae suffered a giant outburst about 150 years ago, when it became one of the brightest stars in the southern sky. Though the star released as much visible light as a supernova explosion, it survived the outburst, and now returns processed material to the interstellar medium in two lobes and a large, thin equatorial disk, all moving outward at about 1.5 million miles per hour. Estimated to be 100 times heftier than our Sun, Eta Carinae may be one of the most massive stars in our galaxy.

Lower mass stars like our Sun evolve sedately. As they run out of hydrogen fuel in their cores, they slowly expand to become “red giants,” relatively cool, very large stars. When the Sun becomes a red giant in some 5 billion years, it will expand to engulf the inner planets of our Solar System. In this red-giant phase, mass is pushed off the surface of stars in “stellar winds” that are the major source of matter for the interstellar medium. Even these lower mass stars contribute to cosmic nucleosynthesis, by production of light elements like carbon and nitrogen. At the end of the red-giant phase, the star itself collapses to become a hot, planet-sized “white dwarf” which slowly cools as it radiates away its stored energy.

Stars are the factories for new elements in the Universe and, by the energy that they deposit there, mix the raw material for succeeding generations. The SEU theme is committed to mapping the processes by which these stellar factories build up the Universe.

Bringing it all Together in Galaxies

The observable Universe contains about one hundred billion galaxies, each one an immense ensemble of about one hundred billion stars and attendant gas, all held together by gravity. Our own Milky Way is typical, but galaxies span wide ranges in sizes, shapes and demographics. One of the most important goals in contemporary astronomy is to determine how and when galaxies were formed, and why they have the properties that they do. SEU missions will trace their evolution from the primordial structure that the Universe was born with all the way to the intricate systems of the kind that we are part of today.

Fountains of new elements spraying into the Universe…

This HST snapshot of the galaxy NGC3079 reveals dramatic activities in the core where a bubble of hot gas is rising above the galaxy disk. The bubble is likely being blown by winds from a burst of star formation. Gaseous filaments at the top of the bubble are being expelled into intergalactic space. Eventually, some of this gas will rain down on the disk to form new generations of enriched stars. This picture illustrates rampant star formation in a nearby galaxy, and the exchange of processed gas with the intergalactic medium surrounding it.

We also want to understand the role played in this evolution by the super-massive black holes that today lie mostly dormant in the hearts of galaxies. We know that when the Universe was a much younger and more violent place, these super-massive black holes were gorging themselves with surrounding material and growing in a natal feeding frenzy. The remaining signposts of this black-hole birthing process are the enigmatic and fascinating quasars and related active galactic nuclei.

The challenges are daunting, but several approaches are promising. The first – our galaxy archaeology – involves sifting through the fossil record in nearby galaxies. Just as taking a human census would allow us to chart the history of human births over the last century, the census of stars in a galaxy allows us to determine the history of stellar births over the history of the Universe. The second approach uses telescopes as time machines. As we peer farther out into the Universe with ever more sensitive instruments, we peer back in time. This allows us to chronicle the properties of galaxies at different epochs over the history of the Universe, and thereby understand how and when galaxies were formed. The third approach is to intensively study examples of current galaxy-building in our local Universe: how do stars form in galaxies and how do these stars seed the cosmos with light, heat, and the chemical elements from which planets and life are made?

The plan for the SEU theme takes three concerted approaches -- cosmic archaeology, looking at the Universe long ago and far away, and understanding contemporary mechanisms of galaxy building .

The Space Astronomy Imperative

A detailed understanding of stars and galaxies --their nucleosynthesis, winds, radiation and gravity fields -- constitutes the foundation of the SEU theme charter, which is to decipher the structure and evolution of the Universe. Space based telescopes have achieved unique advantages and opportunities in this regard. Different spectral regions probe vastly different physical regimes. Rather than peering at the cosmos through narrow and limiting spectral bands that our atmosphere transmits to ground-based telescopes, we can from space choose our view based on information gathering potential. The stability of space platforms allows precision pointing, and opportunities for the clearest views of the Universe. Their thermal isolation allows for cryogenic telescopes, which can provide the highest sensitivity. This roadmap emphasizes how the maturation of our technological capabilities and research perspective has focused our attention on answering key problems that build this understanding.

** The order of the following science sections has not yet been decided. When we come up with a rationale for ordering them, that rationale will be referred to here. **

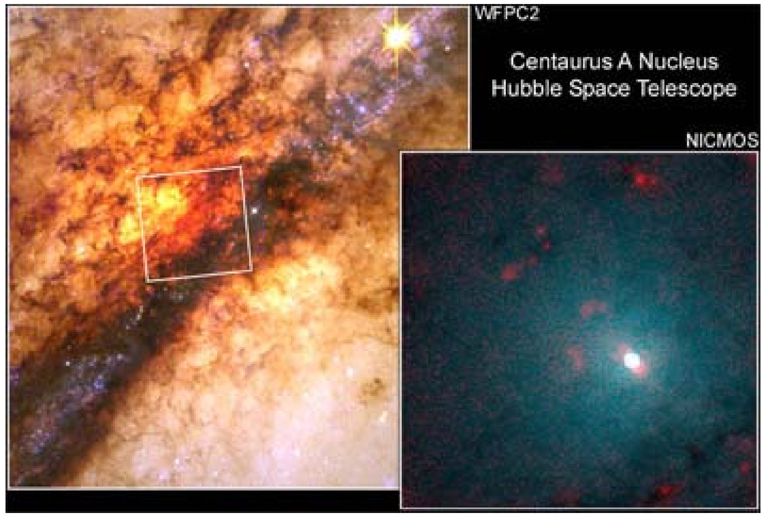
Of New Stars and New Galaxies

New space observatories will provide a census of the first galaxies, and detect and explore the dynamics of pre-galactic clouds as they cool and collapse into stars. We are just beginning to learn how star formation takes place locally, and similar considerations apply to the larger scale phenomena of galaxy formation, and the interaction between galaxies and the intergalactic gas. The birth of stars out of interstellar clouds has been mapped out in some detail in our own and nearby galaxies using infrared telescopes. The dusty visually opaque cocoons out of which all but the earliest generations of stars are formed are relatively transparent in the infrared, so such telescopes allow us to watch the process happen. The signatures of these epochal birthing events have now been detected in the distant Universe. There we may in fact be seeing the first such generations of stars following the formation of their host galaxies out of concentrations in the primordial soup of matter.

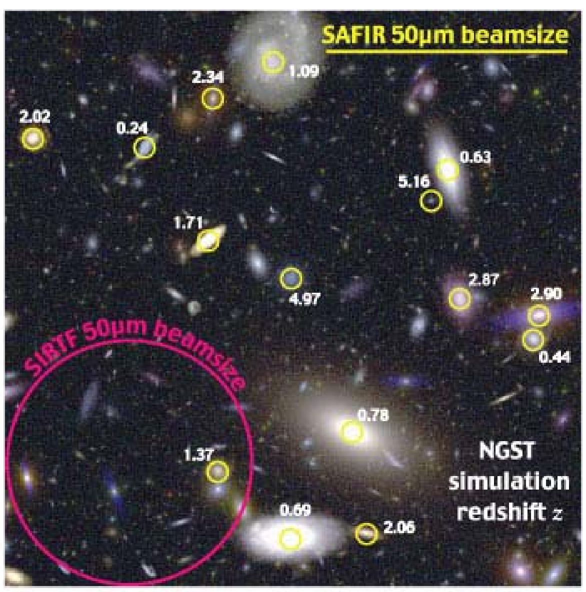
These measurements will build on our new understanding of the detailed distribution of the microwave background from missions like the Microwave Anisotropy Probe (MAP) and Planck, allowing us to explore the emergence of galaxies out of the primordial structure which is the relic from the birth of the Universe. These missions pick up the first light that escaped this Big Bang. The first generation of stars were composed of only hydrogen and helium so the penultimate stage of the first collapses of clouds into stars will be dominated by warm dense hydrogen gas, most likely in molecular form. Light from molecular hydrogen is emitted at infrared wavelengths that are detectable only outside the Earth's atmosphere. A cryogenic, large aperture infrared observatory like the Single Aperture Far Infrared (SAFIR) observatory would offer a unique window into galaxy collapse before stars form and cosmic nucleosynthesis begins. Such a mission could build upon Next Generation Space Telescope (NGST) technology and was recently endorsed as a high priority by the community Decadal Survey.

Glimmers of secrets through the murk …

The infrared transparency of a nearby dust enshrouded galaxy (Cen A) is illustrated by this HST optical image at left with the near infrared NICMOS image of the nuclear region inset at right. The central engine of this galaxy is clearly revealed at infrared wavelengths.



For galaxies in the very early Universe, one of the first major changes after starting the stellar element-building machinery is dust grain formation. Condensable and refractory elements that come out of the first generations of stars become the smoke and soot of the interstellar medium. This interstellar dust becomes a major source of galactic opacity, absorbing much of the optical and ultraviolet light. These grains reradiate this absorbed energy in the infrared, so actively star forming galaxies are brightest at these long wavelengths. For sources at cosmological distances, the expansion of the Universe shifts their peak energy towards even longer far infrared and submillimeter wavelengths. Since the spectral peak moves closer to these spectral bands as we look at galaxies farther away, they don't get fainter as quickly with distance as they do at other wavelengths. This remarkable property makes far infrared and submillimeter probes especially powerful as cosmological tools.



Details of a distant youth …

The infrared beams (spatial resolution) of a 10m cold far- infrared telescope (small yellow circles) are superimposed on a simulated NGST image. Extragalactic targets for this large far infrared telescope are shown under these yellow circles, with their vast redshifts indicated. The large red circle shows the beamsize of SIRTF, which is too large to distinguish individual distant galaxies. The large cold telescope would clearly isolate, and even resolve many of the newly born galaxies at the edge of the Universe.

The initial seeding of infant galaxies by first generation stars with newly created elements results in bright emission lines of light ions, such as C^+ at a wavelength of 158 microns and N^+ at 122 and 205 microns. These spectral lines are beacons that are not only superb probes of redshift distances in very remote galaxies, but are also powerful coolants of interstellar clouds. In this latter regard, they provide for diffuse clouds of material what water and CO provide for denser regions in which the collapsed has progressed further. By enhancing the cooling rate, these lines allow the clouds to collapse more quickly, thus accelerating the star formation process.

Both the infrared and ultraviolet offer a rich suite of diagnostic spectral lines for chemical characterization of interstellar and circumstellar gas out of which these stars will be formed. These bright lines offer the opportunity for high spectral resolution that will allow us to measure the orbits and flows of this gas in detail, tracing the flow from cloud to protostar. Submillimeter interferometers in space will offer orders of magnitude improvement in image clarity over that currently available, complementing the huge increases in sensitivity that the single dish instruments will provide. Such observatories will take the next scientific leap beyond that of the Space Infrared Telescope Facility (SIRTF), the Stratospheric Observatory for Infrared Astronomy (SOFIA) and Herschel, which will set the scientific and technological stage for future efforts. They will complement the longer wavelength ground-based investments such as the Atacama Large Millimeter Array (ALMA), which is sensitive to the cold component of the interstellar star-making material. Building on the results of the Hubble Space Telescope (HST) and the Far Ultraviolet Spectroscopic Explorer (FUSE), large aperture ultraviolet telescopes in space will, though larger collecting area and improved detectors, greatly increase the number of detectable background sources defining pencil beams that probe the interstellar medium of our own Galaxy on different lines of sight.

Of fundamental importance to our program is the role that stars play in the chemical and energy evolution of the Universe. This line of inquiry is aimed at understanding both the mechanisms of stellar nucleosynthesis, and the history of stellar populations. When and how were the first stars formed, and what can contemporary star formation teach us about it? How were galaxies built, and can we chronicle the epochs of star formation in them?

Seeing the earliest stars in the earliest galaxies is now within our technological reach. We will build telescopes that will do this, and efficiently detect and assay interstellar gas out of which these stars are made.

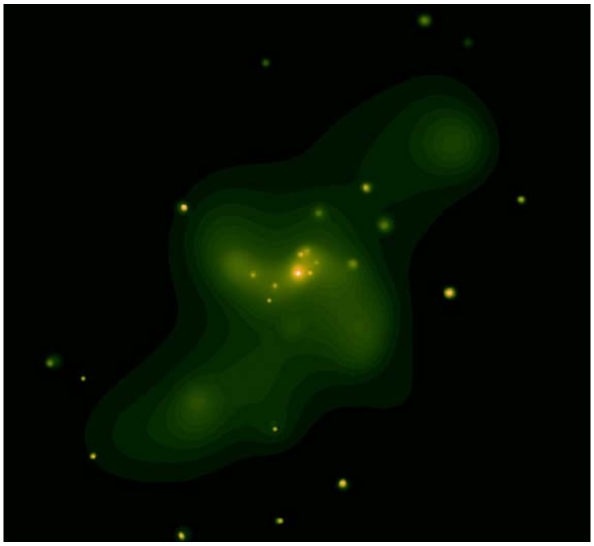
Light and Wind from the Heart of the Beasts

This roadmap features a focused program (“Beyond Einstein”) on the detailed structure of collapsed objects and the physics of spacetime around them. These objects also play an important role in the large scale structure and evolution of the Universe, especially in its early history, and the SEU theme is committed to deciphering this role.

In recent years there has been abundant observational evidence, much of it garnered from SEU space missions such as the Chandra X-ray Observatory and the Compton Gamma Ray Observatory (CGRO), to support the hypothesis that gas accretes onto compact objects (black holes, neutron stars, and white dwarfs) via accretion disks. For stellar-sized objects, the gas is gravitationally sucked off of a companion star. For the massive black holes that we believe to be the central engines in all “active” galactic nuclei (AGN), which include quasars, the gaseous fuel comes both from the central star cluster and interstellar gas that simply settles into the galactic nucleus. In many cases, we believe that this fuel is diverted from stable orbits around the hole into the hole by a violent kick from a burst of nuclear star formation. As this gas falls deeper into the gravitational potential well of the black hole, its energy is converted into heat through dissipative stresses and then into powerful radiation. This radiation can be seen directly with high energy telescopes, or indirectly with infrared and radio telescopes that measure the surrounding gas that it heats. Almost half of the mass falling into a black hole can be radiated as energy, and this huge energy output can manifestly influence the galaxy that harbors the black hole.

Revealing gravitational rogues inside galaxies …

Chandra's X-ray image of the galaxy NGC 1553 reveals diffuse hot gas dotted with many point-like sources, which are due to black holes and neutron stars in binary star systems. The bright central source in NGC 1553 is probably due to a supermassive black hole in the nucleus of the galaxy. The nature of the spiral feature curling out from either side of this source is not known. It could be caused by shock waves from a pair of bubbles of high energy particles that were ejected from the vicinity of the supermassive black hole.

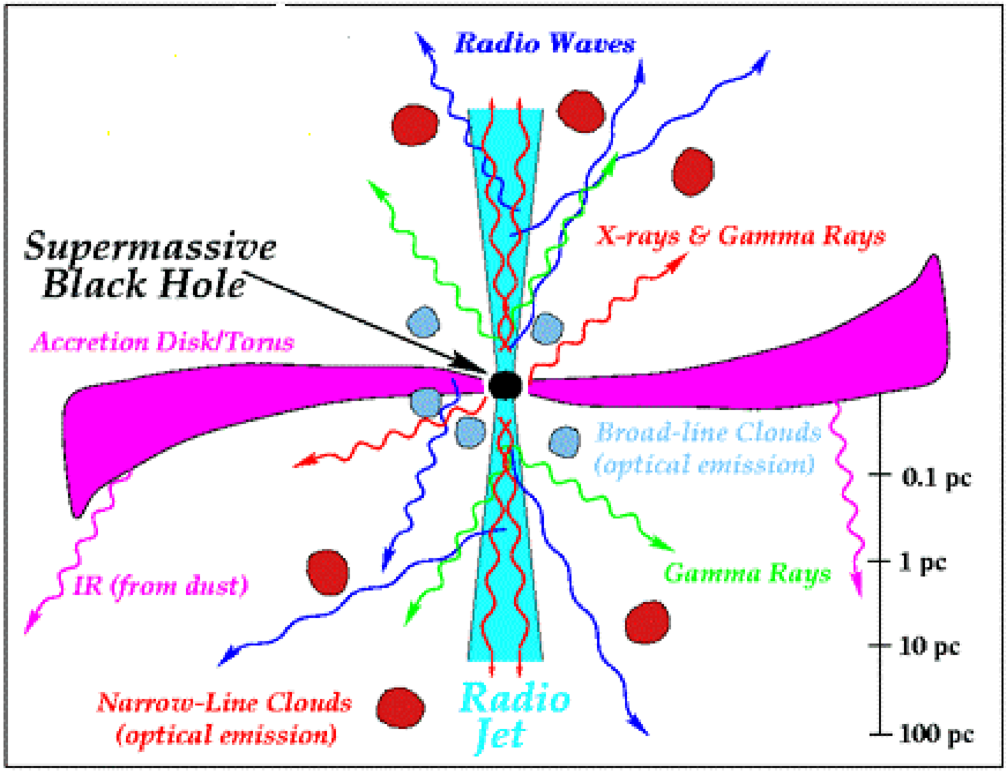


One of the main impediments to studying these nuclear furnaces, whatever their size, is the galaxy that surrounds them. While the dust and gas in the host galaxy constitutes the fuel for the beast, its material also veils it. For this reason, observations at long (infrared and radio) and short (X-rays and gamma rays) wavelengths that can penetrate these clouds are powerful investigative strategies. The Gamma Ray Large Area Telescope (GLAST), now in development, will use high energy gamma rays to see the most energetic regions of black hole environs.

The most powerful active galactic nuclei are called quasars. These are so bright that they outshine the surrounding galaxy, and can be used as beacons with which to probe the Universe. For many non-AGN galaxies, there is good evidence that they still harbor giant black holes at their centers. These quiescent black holes, which unlike their AGN counterparts are presently deprived of infalling fuel, may still dominate the gravitational field of the inner galaxy, and drive rampant star formation in the gravitational potential well. The high luminosities of AGN make it possible to observe these systems at very great distances, thereby providing fundamental information about the formation and early evolution of galaxies. Powerful AGN were far more common in the early Universe, and their numbers peaked during the AGN epoch at redshifts of 2 to 3, when the universe was only 20% of it's present age. A more powerful visible-light successor to HST could be used to study the environments of AGN during this epoch in the rest-frame ultraviolet (the most direct probe of the young stars that might accompany the joint formation of a supermassive black hole and its host galaxy).

What is the origin of these supermassive black holes at the cores of galaxies? Did they form from the merging of smaller black holes created at very early epochs, or were they first formed with their large masses? New X-ray and infrared observatories, building on the foundation set by

Chandra and SIRTF will be able to detect such supermassive black holes all the way out to the edge of the Universe (even if they are shrouded by natal gas and dust that obscures them from view at visible wavelengths). Such a cosmological census of black holes is necessary to understand how the gas in the early Universe was first heated, which in turn affects the formation of galaxies from this gas.

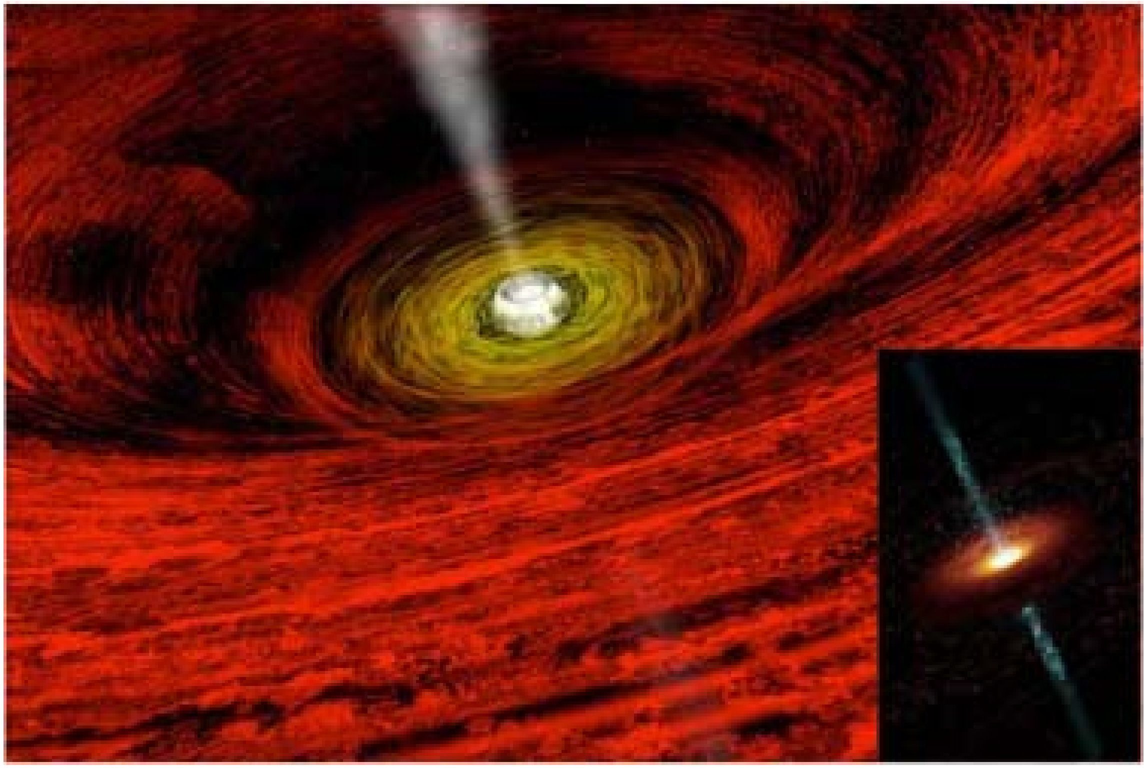


Since the accretion disk is the collector and mediator of the fuel supply onto collapsed objects, our understanding of AGN (as well as the stellar analogues noted above) depends critically on our ability to figure out how these disks work. Observations with new generation instruments will give us visibility into the accretion disks of supermassive black holes that feed quasars. Observations of lower power (but much closer) AGN are even now allowing us to see the inner parts of these accretion disks and to understand how gaseous fuel is funneled to the central black hole.

X-ray spectroscopy is particularly powerful tool with which to probe the inner-most structure of AGN and their accretion disks. This is for two reasons. First, the X-rays originate in the regions very close to the black hole. Second, there are relatively strong features in the X-ray spectra of AGN that provide crucial diagnostic information. In fact, analysis of the temporal variations in the X-ray spectra can be used to perform a kind of "AGN-tomography": a detailed mapping of the material surrounding the supermassive black hole. This is a key objective of missions like Constellation-X in the "Beyond Einstein" initiative.

A complementary approach is provided by very long baseline interferometry (VLBI) radio maps. This technique that has been pioneered and refined from the ground allows radio-emitting material near the black hole to be directly mapped with a resolution over a hundred times better than the HST achieves at visible wavelengths. Recent VLBI maps of AGN have detected intense water emission lines, amplified by a natural maser process, from several of these local sources. This has enabled us to measure the mass of several central black holes with unprecedented accuracy.

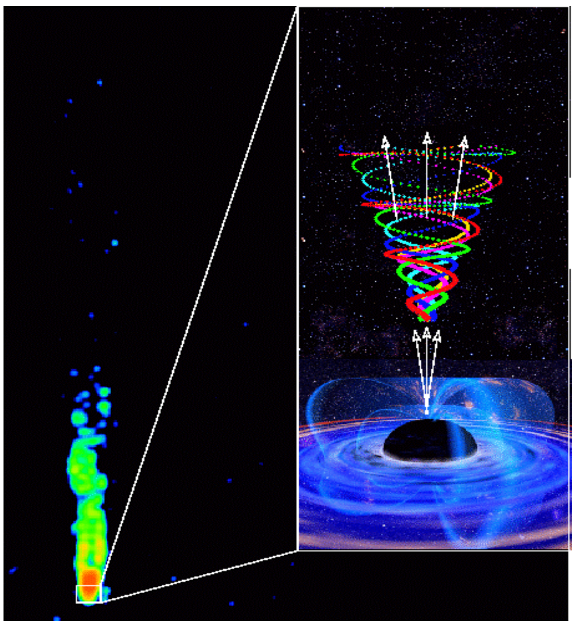
Swirling disks of death around black holes …



In this artist's rendering, gas spirals into an accretion disk around a supermassive black hole at the core of a galaxy. The gravitational energy liberated by the infall causes the central region of the disk to become fiercely luminous, and it drives a jet of material outward along the polar axes of the galaxy, which is seen in the inset.

The full power of radio interferometry will not be realized until interferometry from space can provide, through longer baselines and accessibility of shorter wavelengths, more detailed views of molecular interstellar material falling into these accretion disks. Such views would include both small black holes in our own galaxy and supermassive black holes at the centers of distant galaxies. The viability of space interferometry has been demonstrated with the recent Japanese HALCA mission. With multiple platforms in highly elliptical orbits, achievable baselines for proposed new missions such as the Advanced Radio Interferometry Between Earth and Space (ARISE) telescope, which was recently endorsed as a high priority by the community, would not only resolve accretion disks out to almost 200 Mpc, but probe the very event horizon of the closest supermassive black hole in the galaxy M87. Using the H2O megamasers in the outer accretion disk as tracers, these telescopes will accurately map their orbits, and use these orbits to deduce accurate distances and central masses for this large sample of supermassive black holes. Such measurements will complement the dynamical measurements of the inner accretion disks of black holes by "Beyond Einstein" missions such as Constellation-X.

Such accretion disks around black holes are understood to drive powerful outflows along their polar axes. These strong winds are somehow efficiently collimated into "jets" that transport energy outward from the accretion disk and effectively clear away the raw materials of star formation in these directions. As a result, even small accretion disks can influence, in a major way, the global properties of star formation in a galaxy. Understanding how these jets are made, and what role they play in the accretion process is a major unsolved problem. Are these pencil-thin jets launched and collimated by magnetic fields, or perhaps by the powerful radiation fields in the disks? While these jets have now been observed throughout the electromagnetic spectrum, from radio observations with the VLBI telescopes from the ground and space, through the infrared and optical, all the way into the X-ray and gamma ray regime, new telescopes with vastly increased sensitivity and clarity of view will be used in a coordinated way to understand the energy source, and the acceleration and confinement mechanisms of what are essentially cosmic cannons.



Firing celestial beams of matter …

The large improvement in spatial resolution of space radio interferometry over that accessible from the ground allows the inner parts of nearby galactic accretion disks, and even event horizons of nearby black holes to be probed. At left is a high resolution VLA image of the jet flowing out of the supermassive black hole in the galaxy NGC4158. At right, an artists conception of the launch region of the jet, with the event horizon of the black hole at center. It is this vastly smaller scale that space interferometry will probe. Such images will give new understanding to the origin, acceleration, and collimation of the flow.

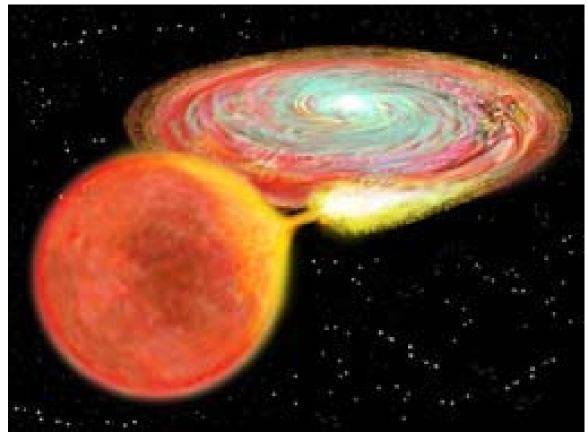
Detailed comparison of the morphology of star formation in galaxies with active nuclei will be needed to investigate the roles that accretion disk-driven winds and point-like gravitational fields have on the formation of stars in, and the evolution of galaxies.

Peering into the hearts of galaxies, we will use new telescopes to study the powerful flows of matter and radiation that emanate from the massive black holes at their cores.

Understanding Nature's Flash Bulbs to Measure the Universe

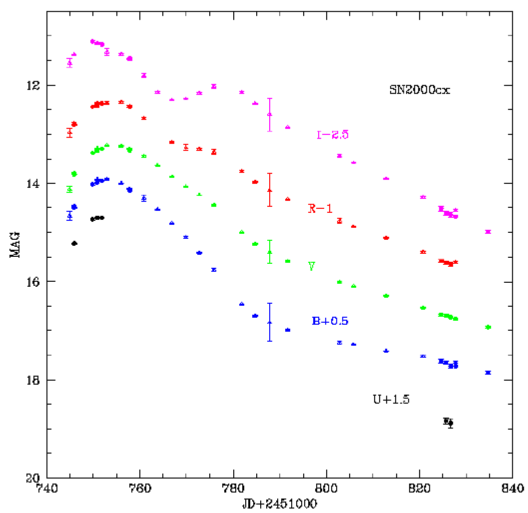
The structure and evolution of the Universe is strongly driven by stellar collapse and explosive events, which inject energy as well as nuclear products into the interstellar gas. The SEU theme seeks to get new insight into the mechanism and detailed properties of these explosions using a new generation of highly capable instruments.

Type Ia supernovae are uniquely important because they are very luminous and have roughly constant peak intrinsic brightness. These cosmic flash bulbs can therefore be used to measure the geometry of the Universe on large scale. Many groups are pursuing surveys for such supernovae from the ground and from space, and early results have led astronomers to the monumental realization that the expansion of our Universe is accelerating. While Type Ia supernovae (SN Ia) appear to be wonderful tools for this kind of work, our ability to use these objects as a calibrated standard candle for cosmology ultimately depends on our detailed understanding of their nature, in particular from nearby supernovae. This type of explosion is thought to be the detonation or of a white dwarf that pulls so much mass off of a a nearby companion that electron degeneracy pressure can no longer support the star against collapse. We lack, however, a fundamental



understanding of the Ia story. We cannot understand the evolution of their properties over cosmic times without successfully modeling their nuclear burning and dynamics. Open questions include the composition and mass of the progenitor, the nature of the triggering process, the location of the initial detonation in the star, the propagation mechanism of the nuclear burning in the explosion, and the dynamics and structure of the ejecta, including the way that it is mixed.

Explosive burning of the white dwarf can release large quantities of newly formed elements into the interstellar medium. This seeding can be traced through the nuclear line emission of radioactive isotopes, which are produced prodigiously in the explosion. We will see a 158 keV gamma-ray emission line from ^{56}Ni and a line from ^{56}Co at 847 keV as these isotopes decay. By



SN2000cx is a Type Ia Supernova located in the outer part of NGC 524 at about 35 Mpc distance, and is below and to the right of the brightest star in the figure on the right. Gamma ray observations can determine how much of the light from the supernova (light curves shown at right) is powered by radioactive decays from the isotopes that are formed in the event.

observing and modeling such emission line production from many SN Ia per year, a nuclear line observatory in the low to moderate energy range such as an advanced Compton telescope will provide a much clearer understanding of Type Ia supernovae and their use as a probe of cosmology. The promise of these new technologies is a gamma ray telescope that can detect all Type Ia supernovae out to at least the Virgo Group of galaxies, studies of which are benchmarks for modern cosmology.

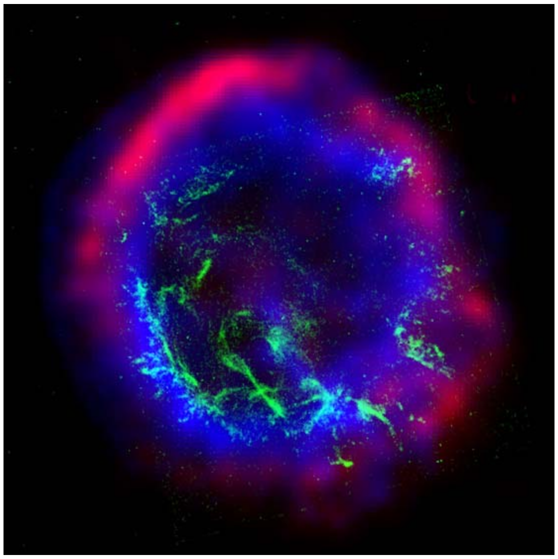
We are ready to understand how the standard candles burn that will light our way to the early Universe.

Thermonuclear Explosions and the Enrichment of Galaxies

The structure and evolution of the Universe is strongly driven by stellar collapse and explosive events, which inject energy as well as a multitude of nuclear products into the interstellar gas. The Ia supernovae described above are but one glimpse of the explosive processes that enrich galaxies. Life as we know it would not be possible without the carbon, oxygen, and heavy metals that are synthesized in stellar interiors and released in these explosions. Winds from massive Wolf-Rayet stars and asymptotic giant branch stars can expel dredged-up, highly enriched materials from the nuclear burning zones in a star. Radioactive elements are formed in detonation and core collapse supernovae, during nuclear burning on white dwarf novae, and even near the alchemy labs that appear in the inner accretion disks of neutron stars and black holes.

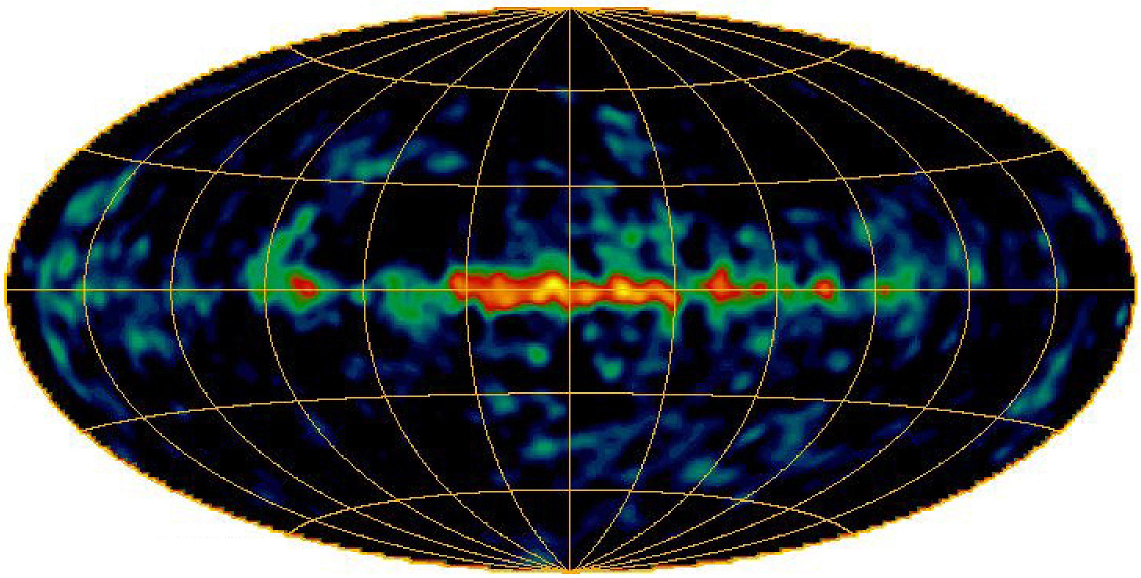
Visions of new elements from a cosmic furnace …

Color composite of the supernova remnant E0102-72: X-ray (blue), optical (green), and radio (red). E0102-72 is the remnant of a star that exploded in a nearby galaxy known as the Small Magellanic Cloud. The Chandra X-ray image, shown in blue, shows gas that has been heated to millions of degrees Celsius by the rebounding, or reverse shock wave. The X-ray data show that this gas is rich in oxygen and neon. These elements were created by nuclear reactions inside the star and hurled into space by the supernova.



An advanced Compton telescope will be used to measure the explosion mechanisms in core-collapse supernovae, giving their use as a tracer of cosmic nucleosynthesis a more secure foundation. While pioneering efforts in this work have come out of the Compton Gamma Ray Observatory, and will be strengthened by the forthcoming INTEGRAL, a dramatic improvement in sensitivity over these instruments is required to measure more than a few supernovae, and to make the measurements on a time scale that is small compared to that of the decay lifetimes of the isotopes being looked at. Recent technical advances appear to offer the necessary improvements to increase sensitivity, lower background, and improve the energy resolution of the detectors. High-resolution maps of these radioactive decay lines in our own Galaxy will give new quantitative insights into the way nucleosynthesis is organized here at home.

Glowing embers of galactic nucleosynthesis …



In this wide angle 1.809 MeV gamma-ray view of the Milky Way Galaxy from the Compton Observatory, bright spots made by radioactive 26Al show clearly. With a half-life of about a million years – short compared with the timescale of nucleosynthesis – the bright spots that concentrate in the inner galaxy must be contemporary sites of elemental enrichment.

Nuclear gamma-ray line telescopes will also play an important role in our understanding of classical novae, in which hydrogen rich material from a close companion is more delicately deposited on massive white dwarfs, and a localized thermonuclear runaway is produced. Even in these much smaller explosions, large concentrations of short-lived isotopes of light elements are produced, and these should be detectable over much of the galaxy. When coupled with high-resolution maps from ^{44}Ti with a half-life of 62 years, and with maps from shorter and longer-lived radioactivities, we will learn where the building blocks of comets, planets, and life are formed.

The discovery and exploration of gamma ray bursts (GRBs) has been one of the most striking and scientifically provocative achievements of the SEU theme in the last decade. Now understood to be extragalactic in origin, these bursts of high energy light from the cosmos outshine, for minutes at a time, the galaxies in which they originate. The revolution in our understanding of gamma-ray bursts resulting from the Beppo-SAX and long wavelength follow-on observations show that GRBs with durations longer than about one second are most likely associated with massive stars and core-collapse supernovae. If a gamma-ray burst occurs when a black hole is formed, then these flashes of gamma radiation signal both the death of a star and the birth of a black hole. Stellar death need not be mourned, however, because a gamma-ray burst points us to the earliest sites of massive star formation. A large field-of-view, high sensitivity advanced Compton telescope will carry on the fundamental studies begun with Beppo-SAX and continued by Swift to search for dim GRBs, both nearby and distant. In coordination with ground-based and space-based optical follow-up studies, these results will examine host galaxy type and chart the star formation rate history of the universe. While GRBs can be detected at many wavelengths, using a gamma-ray telescope will avoid the difficulty of surveys at longer wavelengths where extinction can hide them.

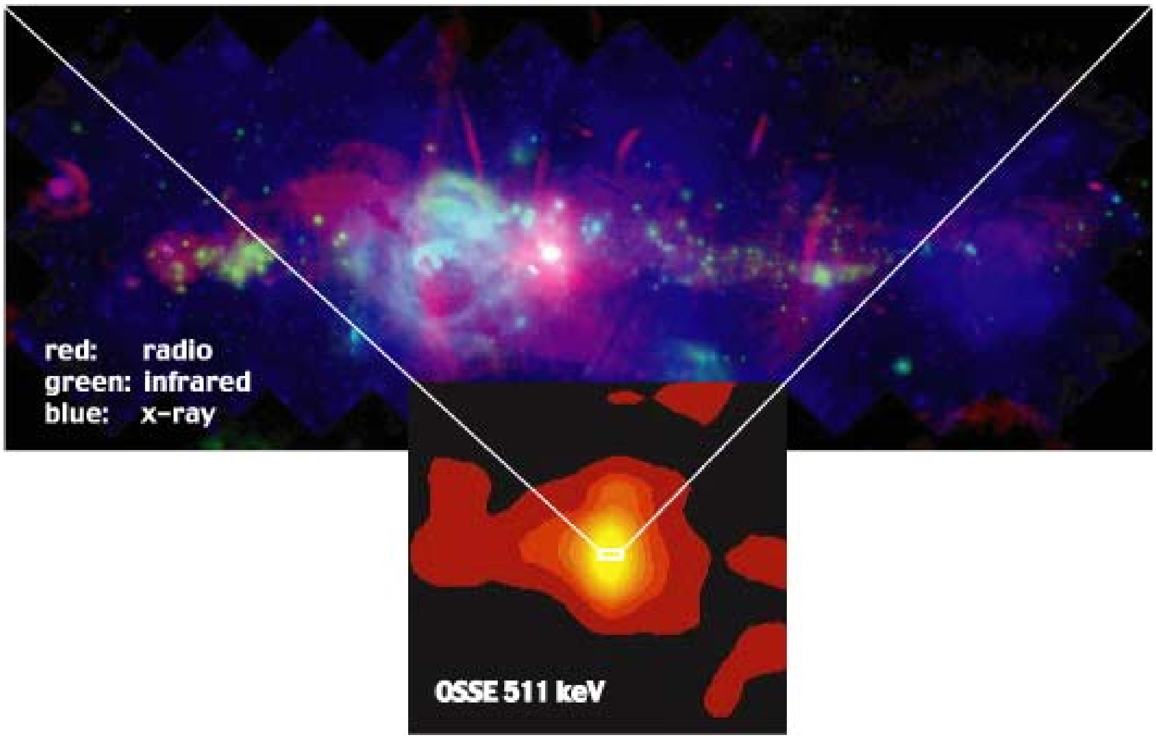
Future telescopes will let us see nucleosynthesis happen, and chart how the Universe gets seeded with the materials out of which we are made.

Visions of Annihilation

Our Universe is asymmetric, and seems to favor normal matter over antimatter in its composition. The amount of antimatter in our Universe remains uncharted, however. While the search for baryonic antimatter can be conducted with cosmic ray and medium energy gamma-ray experiments, our Galaxy, and perhaps our Universe as a whole, is glowing in the annihilation of a lightweight form of antimatter, namely the positron (or anti-electron). In such an annihilation, an electron and its positron counterpart most often directly annihilate into two 511 keV photons. Positrons are not only formed by the decay of radioactive elements manufactured by stars, but also as secondaries in cosmic ray interactions. Large amounts of positron production are theoretically expected from black hole antimatter factories.

Low resolution maps of the Milky Way made by the CGRO in the light of the 511 keV electron-positron annihilation line revealed recognizable features from the disk and inner bulge of our galaxy, as well as evidence for emission concentrated at the center of our galaxy. The origin of these positrons is unclear, but decay of radioactive nuclei is a likely source. It is clear from the annihilation maps that positrons are distributed on a galaxy-wide scale, though the morphology of annihilation radiation doesn't clearly match that of any stellar component. The annihilation emission from compact sources in the Galaxy could be highly transient, which would indicate that the emission is dominated by a few compact sources, for example, the mysteriously quiescent black hole at the dynamical center SgrA*.

Searching for sources of antimatter in a galactic forest …



The image of 511 keV radiation from the Compton Gamma Ray Observatory is shown in the lower image, and covers about ten degrees of the sky around our Galactic Center. This is the highest resolution positron annihilation image available. At top is the wealth of structure in the very center of this region as seen in three different parts of the spectrum. This montage is illustrative of our need for much more detailed images from new generation gamma ray telescopes to identify the sites and sources of antimatter in the inner galaxy.

We look ahead to the opportunity to build new, sensitive low-energy gamma ray telescopes that are designed specifically to search for this annihilation radiation. With vastly higher spatial resolution and sensitivity than what we had in the Compton Observatory, such telescopes will reveal individual sites of positron production in our own galaxy, and measure the production rates in other nearby galaxies. Such a telescope, focused at the center of our galaxy, will establish whether a burst of star formation there is responsible for driving a superwind that is laden with positrons and newly synthesized material.

Antimatter is being produced prodigiously in at least our own Galaxy. We will locate the source and understand how it produces this extraordinary material.

The Mystery of the Missing Matter

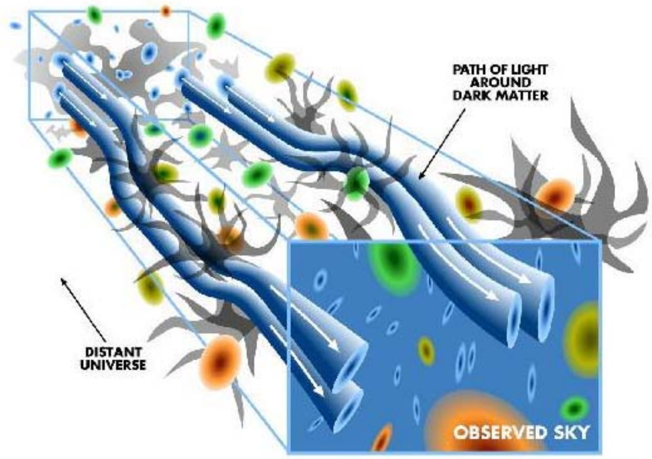
Our models of the Universe predict, with considerable accuracy, many of the important properties that we can now measure. One astonishing exception is the amount of matter in the Universe. According to the best cosmological models the total gravitational mass of the Universe appears to vastly exceed (by about two orders of magnitude) what we can directly account for today observationally in the form of stars and interstellar gas. The “missing” matter takes two forms. The majority (roughly 90%) is in a form that is fundamentally different from the ordinary baryonic matter composed of the familiar protons and neutrons that make up the atoms from which stars, planets, and people are made. Determining the nature of this non-baryonic matter is one of the overarching quests of both physics and astronomy. It is an elusive constituent that neither emits nor absorbs light of any form, and reveals its presence only through its gravitational influence on the matter we can directly see and study. For this reason it is most often called “dark matter”. The second type of missing matter is comprised of ordinary baryons. Estimates based on the measured primordial ratios of hydrogen, helium, and deuterium lead, in a fairly straightforward prediction, to a missing baryonic component that exceeds the total mass in normal stars and interstellar gas today by a factor of 5 to 10.

Making missing matter appear …

The NGC 2300 group of galaxies contains a large reservoir of million-degree gas glowing in X-rays. A false-color X-ray image of the hot gas taken by ROSAT is superimposed here on an optical picture of the galaxy group. Gravity from the luminous parts of the galaxies alone is not enough to keep the gas in its place. There must be large quantities of dark matter whose gravity is preventing the gas from escaping.

Galaxies themselves are dominated by huge halos of non-baryonic dark matter. They can be thought of as gravitational potential wells in which the stars and gas that we see are trapped. In addition to stars, elliptical galaxies contain hot X-ray emitting interstellar gas that extends to radii well beyond where we can see stars. By mapping the density and temperature of this trapped hot gas, we can develop a reliable mass model of the whole galaxy, and trace out where the dark matter resides in and around galaxies. Gravitational lensing effects provide yet another probe of dark matter, by using the unique capability of a space-based wide-field imaging telescope to map the gravitationally-distorted images of distant galaxies lying behind foreground concentrations of matter in galaxy halos, clusters of galaxies, and even larger structures.

The missing baryonic matter is also both important and elusive. Although some could be hidden from us in collapsed quiescent gas clouds or cold stars that are just too dim to see, most is now believed to lie in the vast and nearly empty regions between the galaxies in the form of very tenuous and nearly invisible clouds of gas. Some is perhaps loosely associated with galaxies themselves, and some will trace the vast cosmic web defined by the distribution of intergalactic non-baryonic dark matter. We want to find this missing baryonic material to map out its history and to understand why so little of it was used to build the stars and galaxies that we see. By 2010, galaxy surveys will have outlined the distribution of luminous baryonic matter in the contemporary Universe in fine detail, but the dominant intergalactic component will still be largely unexplored.



Warped images from a clumpy universe

Light rays from distant galaxies travel a tortuous path through a universe filled with a web of clustering dark matter. Every bend in the path of a bundle of light from a distant galaxy stretches its apparent image. The orientation of the resulting elliptical images of galaxies contains information on the size and mass of the gravitational lenses distributed over the light path. Light bundles from two distant galaxies which are projected closely together on the sky follow similar paths and undergo similar gravitational deflections by intervening dark matter concentrations.

An efficient way to locate missing baryonic matter in the darkness of intergalactic space is to look for it spectroscopically in silhouette against the light of distant quasars. The Lyman α line is an exquisitely sensitive probe for cold hydrogen gas, more than a million times more sensitive than the radio 21cm line would be. If the baryonic dark matter is mainly primordial and unenriched by stellar nucleosynthesis such an ultraviolet detection strategy would be the only option since Lyman α is by far the most opaque spectral line among hydrogen and helium -- the main primordial constituents. If the gas is hot and chemically enriched, then large next-generation X-ray and ultraviolet telescopes will be able to see absorption lines from such cosmically-important elements as C, N, O, Ne, and Fe. While these efforts are just beginning with instruments on HST, FUSE, and Chandra, new generation ultraviolet and X-ray telescopes will be required to understand the physical, chemical, and dynamical state of this missing baryonic matter, and chart its history.

Our models of the structure of the early Universe that lead to this conundrum are being continually refined. The “roughness” or “fluctuations” of the cosmic microwave background radiation, which is a relic of the early Universe when it was only 300,000 years old -- the first photons that escaped from the Big Bang -- is a powerful tool for assessing the total mass content of the Universe. First detected by the COBE a decade ago, the recently launched Microwave Anisotropy Probe (MAP) will characterize the scale sizes of the fluctuations and yield far more accurate values for cosmological parameters. The future Planck mission will extend this to smaller scales and look for polarization signatures. As these background fluctuations are on scales up to a few tens of arcminutes, it is essential that our knowledge of the distribution of dark matter be available on a comparable scale. In the case of absorption by intergalactic baryons, the required telescope sensitivity is determined by reaching the requisite space density of quasars. Efforts in the development of dramatically more sensitive UV detectors and high throughput large and lightweight precision mirrors are promising in this regard, and realizable mission concepts have been proposed.

Once we are able to detect and characterize the missing baryonic matter, we will have the first glimpses into the role that it plays in the evolution of our Universe. How does the structure of this material determine how galaxies formed? How did its properties change as the Universe aged? How is baryonic material exchanged between galaxies and the intergalactic medium?

New generation telescopes will be able to locate and assay the both the baryonic and non-baryonic components of the missing matter, answering a longstanding problem with profound cosmological ramifications.

Bullets of the Cosmos

Cosmic rays are an important part of the dynamics and structure of our Galaxy. Most of these high energy nuclei are thought to be hurled to us by supernova shock fronts, perhaps from spallation off of dust grains. The overall distribution of cosmic-ray energies is remarkable in that it is almost a constant power law over at least 13 decades in energy and 31 decades in flux. A small steepening, or "knee," in the slope of the power law energy spectrum of cosmic rays near 10^{15} eV is thought to be associated with the maximum possible energies achievable by direct supernova shock acceleration of cosmic rays. The Advanced Cosmic Ray Composition Experiment for Space Station (ACCESS) will directly explore the connection of cosmic rays with supernovae by identifying these high energy nuclei. This mission has been recently endorsed as a high priority by the community.

An early observer is terrorized by a cosmic "ray". These mysterious high energy beasts have threatened the Earth since its beginning. Their origin is unknown, and their aerodynamic profile seems better adapted to this planet than to interstellar space. They are much more compelling, however, than diagrams of air showers or log N-log E energy spectra. (With apologies to Compton GRO graphic artists.)

As we move to higher energies, the mystery deepens. In fact, we can measure the cosmic-ray spectrum all the way up to ~3 10^{20} eV, where individual particles have the energy of a well-hit baseball! About the only conceivable sources for these particles are galactic nuclei, the giant extragalactic double radio sources or the same mysterious sources as the gamma-ray bursts themselves. A related problem is that scattering off cosmic background photons should render the Universe fairly opaque to these highest energy particles. On a cosmological scale, they must come from sources that are relatively nearby. It has been suggested that these highest energy particles may come from the annihilation of topological defects formed in the early Universe. Here the problem is that the detection rate of these particles is so low that we see too few of them to describe their properties well. Space instruments capable of monitoring large areas of the Earth's atmosphere for the showers that these rare particles produce will establish the energy spectrum of these highest energy cosmic rays and are likely to determine directions to their sources.

Cosmic rays are a window into how nature can channel enormous power into individual atomic nuclei. New observatories will reveal how our Universe is able to act as an extreme particle accelerator, the power of which is unapproachable on Earth.