G A L A X I E S

ORIGINS

S C I E N T I F I C   G O A L S

In this century, we have learned that our Milky Way galaxy, a massive pinwheel of stars and gas bound together by gravity, has been the birthplace of many generations of stars, and presumably, many planetary systems like our own. Theoretical models of the Big Bang, the violent event that gave rise to the Universe, as well as observations of old stars, demonstrate that when the Universe was young, there were no heavy chemical elements such as carbon, nitrogen, and oxygen. Over billions of years, interstellar gas has been recycled and enriched in heavy chemical elements that were created in the nuclear furnaces that powered earlier generations of stars. These heavy elements are the building blocks of Earth-like planets and they are the key ingedients leading to the emergence of life.

Although star formation may have occurred in a pre-galactic Universe, it is likely that the binding together of galaxy-sized units was a necessary step in building up the abundance of heavy elements to the point where the formation of Earth-like worlds, and life as we know it, became possible.

The modern era of the Universe began, then, with the formation of galaxies. The building of complex chemistry and biology has depended on the cooling, concentration, and enrichment of gas within galaxies, a process begun a few hundred million years after the Big Bang. Even though we endeavor to trace the process that led to our existence all the way back to the Big Bang, our origins sensibly begin with the formation of the Milky Way. The building of such enormous structures from a near-featureless Universe, and the manufacture of vast quantities of heavy chemical elements, are essential steps on the road to life.

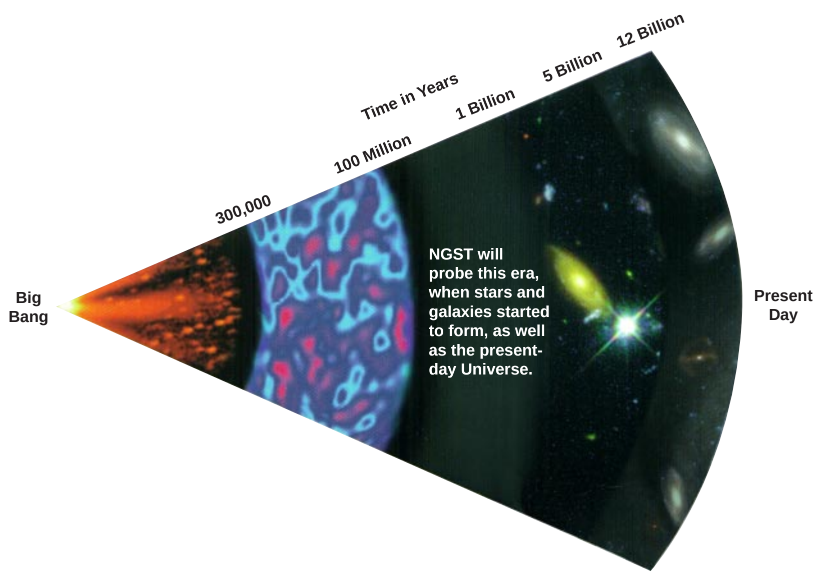
1 TO UNDERSTAND HOW GALAXIES FORMED IN THE EARLY UNIVERSE.

OBJECTIVE 1 • Determine the role of gravity in the emergence of galaxies from the almost perfectly smooth particle sea of the early Universe.

Astronomers have a general concept for how gravity, acting on weak ripples in an otherwise smooth distribution of matter left by the Big Bang, acted in a hierarchical fashion to build larger and larger units. However, the ordinary atomic matter that makes up stars, planets, and people is only a small fraction of the matter in the Universe. The majority, perhaps a sea of exotic elementary particles, is likely to have played the key role in assembling the first galaxy-sized masses. In this theory, discrete masses the size of modern galaxies began to appear somewhere between 100 million and 1 billion years after the Big Bang. Soon after came the first of generations of stars that would produce the heavy chemical elements necessary for the formation of planets and the existence of life. Aspects of this theory have already been confirmed.

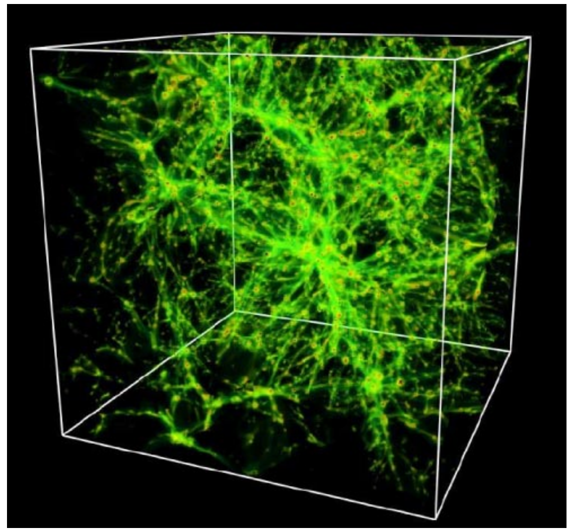
The first evidence of ripples in the distribution of matter in the early Universe was detected by the COBE satellite and by ground-based and balloon-borne radio telescopes. Using the Hubble Space Telescope (HST), the Keck Observatory, and other giant ground-based telescopes, we have detected galaxy-sized, star-forming systems that were in existence some 1 to 2 billion years after the Big Bang, about 90 percent of the way back to the beginning of the Universe. Our goal is to explore all the steps of this process in detail, from the formation of the first ripples to the agglomeration of large masses with copious amounts of star formation. This will require accurate mapping of the amount, distribution, and chemical content of gaseous matter in the early Universe, and the detection of starlight from the earliest stellar generations in the Universe.

NGST will probe back in time to the birth of the first galaxies.



INVESTIGATIONS FOR OBJECTIVE 1

Investigation 1: Determine the fate of baryonic matter as the Universe evolves.



Computer models try to reproduce the 3-D distribution of the galaxies we see, and the dark matter we have not yet observed directly.

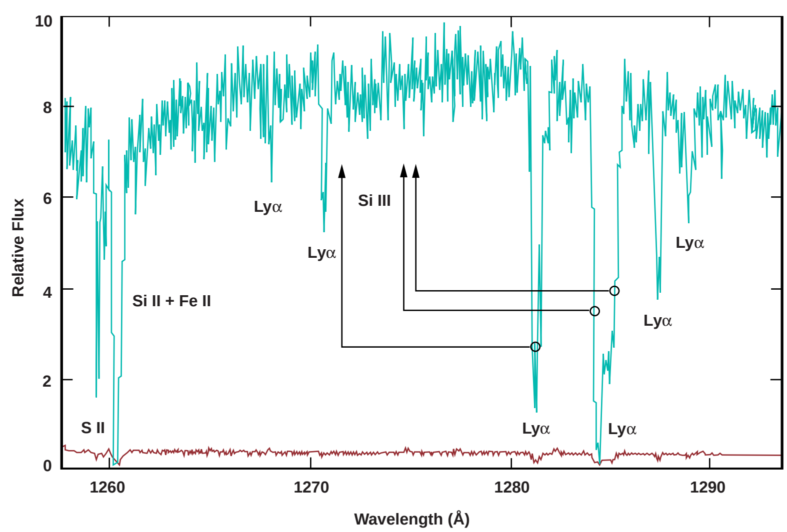
Current observations of the abundance of the light elements (H, D, He, and Li) indicate that in our Universe, baryons — normal matter — contribute only a small fraction, something between 0.5 and 5 percent, of the matter that would be needed to halt the expansion of the Universe. This amount of normal matter is also only around 20 to 25 percent of the total matter that is suggested by current cosmological models and observations of distant supernovae. Spectroscopic observations of deuterium abundances suggest that most of the baryons in the epoch $1 < z < 4$ were still in the form of diffuse, ionized gas in the intergalactic medium. Today, the inventory of baryonic matter appears seriously incomplete: most of it is not found in either the luminous stars or the gas now residing in galaxies.

Is a significant fraction of baryons locked up in the formation of long-lived, low-mass stars or brown dwarfs? How much of the baryonic matter is hidden in the low-luminosity, low-density galaxies that are difficult to detect against the bright-sky background imposed on Earth-bound telescopic observations? Is most baryonic matter still in the form of hot gas, bound within the centers of clusters of galaxies, or cold molecular hydrogen, easily detected in galaxies with active star formation, but almost "invisible" in quiescent galaxies? What is the ionization history of the unclustered gas? New observational techniques, refined cosmological models established by further research on the cosmic microwave background by the Microwave Anisotropy Probe (MAP) and Planck missions, and the increasing sophistication of theoretical computer simulations promise to complete our understanding of the fate of the baryonic matter.

Probing the baryonic content of the Universe as it evolves requires a broad imaging and spectroscopic capability from the ultraviolet to the infrared. For objects like cold white dwarfs, brown dwarfs, and dwarf galaxies, sensitive imaging in the visible and infrared with moderate spatial resolution on the order of 10 arcsec or better, over wide fields of view (many square arcminutes) will be needed to probe the populations in the galactic halo. Ongoing infrared surveys such as the Two-Micron All-Sky Survey (2MASS) and Sloan Digital Sky Survey (SDSS), along with Explorer-class space missions, will provide an inventory of low-mass objects in the neighborhood of the Sun.

Most of the baryons may still be in a gaseous state. The superb sensitivity of a 15- to 25-m IR telescope in space (such as the FAIR mission suggested in this Roadmap) operating between 30–300 μm, and high-resolution, ground-based millimeter interferometers such as the Atacama Large Millimeter Array (ALMA), will reveal the molecular gas conditions in the vicinity of dust-enshrouded, star-forming regions in the early Universe. Deep imaging by Chandra of the 1–10 keV X-ray band will reveal the hot

Clouds of diffuse gas lying between galaxies are detected in absorption against the UV light of distant quasars.

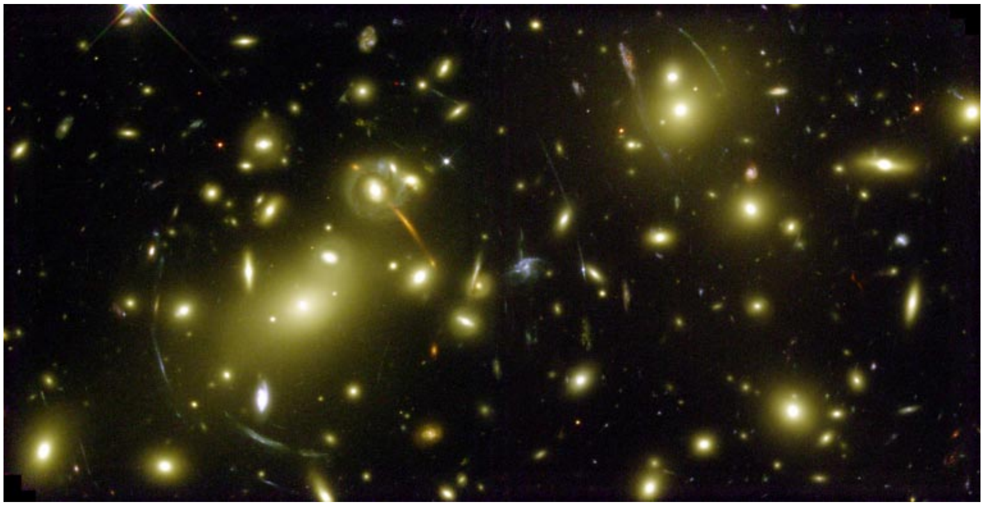


gas (T > 10,000,000 K) within clusters of galaxies and surrounding massive elliptical galaxies. To find and study the gas in the temperature range (1000 K < T < 50,000 K) requires UV–Vis–NIR spectroscopy with low spatial resolution (~1"); both the UV and the NIR require space missions. Modest spectral resolution (R~1000) is required for studying emission from gas clouds at high redshift, but higher resolution (R > 20,000) is needed to extract the maximum information from UV studies of the absorbing gas, such as the Lyman alpha clouds that we observe in the light from distant quasars. The Cosmic Origins Spectrograph (COS) on HST will probe the neutral gas in the intergalactic medium at the current epoch. The SUVO telescope is UV-optimized to detect even lower column densities and to trace the 3-D structure of the diffuse intergalactic gas.

The total mass in baryonic and nonbaryonic structures (galaxies, clusters of galaxies, and even nonluminous, dense regions) can be uniquely estimated from the gravitational bending of light from background galaxies, or "weak lensing." Detecting these distortions in deep images requires the excellent angular resolution (< 0.1 arcsec), extreme sensitivities over a wide wavelength range (λ = 0.4-4 µm), and the stable imaging properties of a space observatory. Both NGST and SUVO utilize a wide field of view to probe the distributions of mass on both larger and smaller scales and over a wider range of redshift (0.5 < z < 3) than those observed with HST.

Investigation 2: Measure the luminosities, forms, and environment of galaxies back to the epoch of their formation.

How do galaxies form and grow? How is the rate at which galaxies develop controlled by their large-scale environment? What controls the relationship between visible, baryonic matter and the invisible, dominant dark matter? What processes control the variety of morphological types of galaxies? At what cosmic epoch did

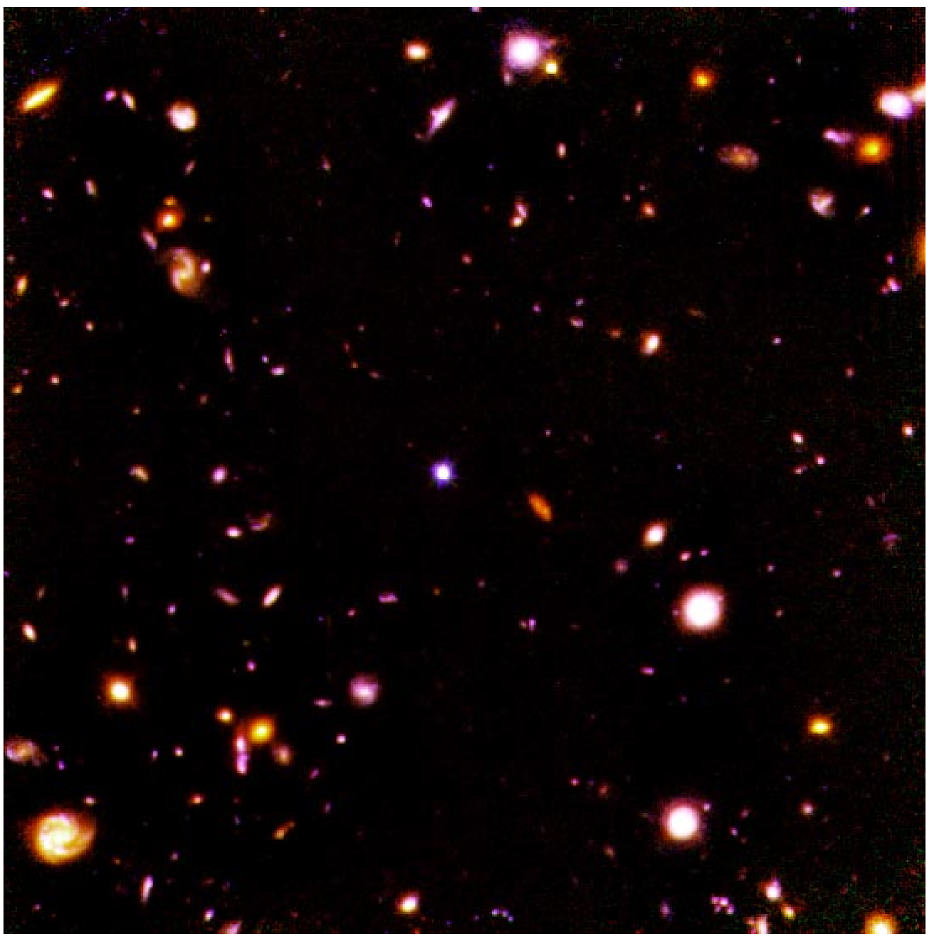


The gravitational pull of this galaxy cluster distorts images of background galaxies.

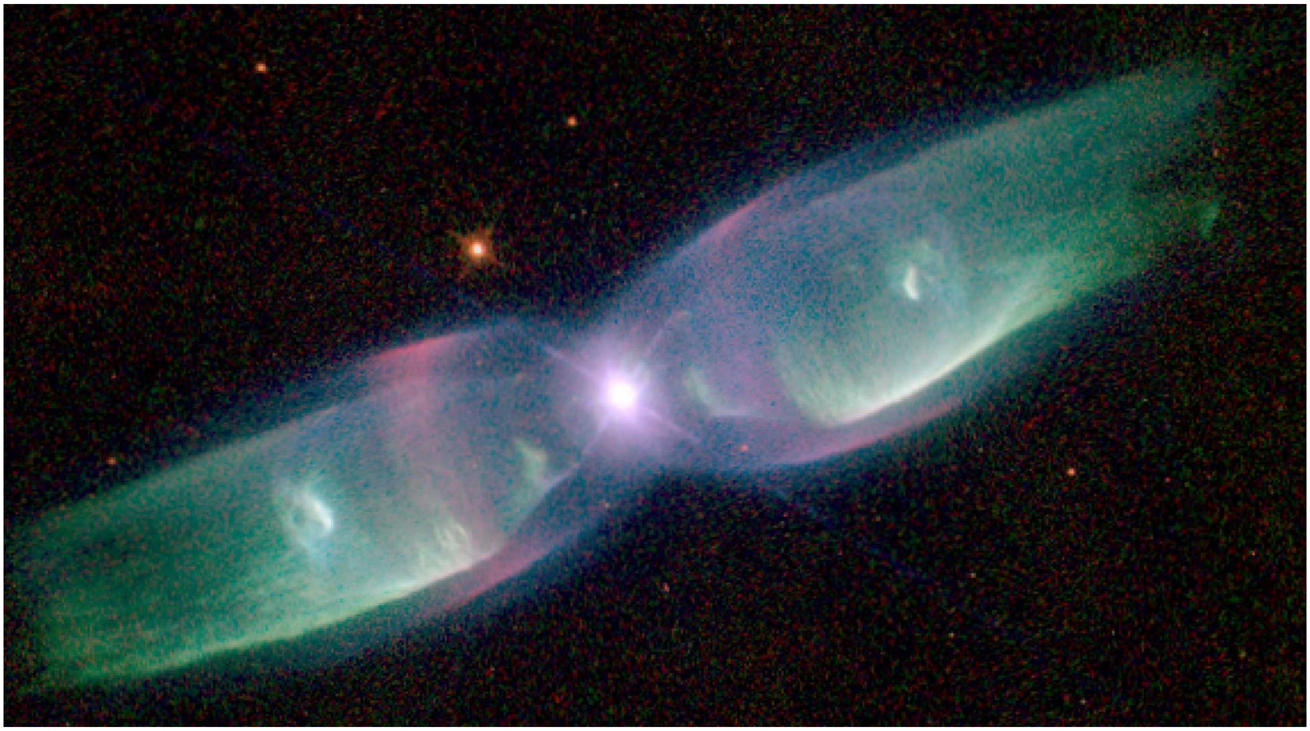
the first substantial star formation in galaxies commence, and what are the present-day descendents of these earliest sites of star formation?

The answers to these and other questions related to galaxy formation require measurement of the luminosity distribution, structure (size, morphology, mass), and clustering of galaxies, through cosmic time and back to the emergence of large star-formation regions in the early Universe. Because of the need to look far back in time, and therefore to significant redshifts, the answer will be found in near- and mid-infrared high sensitivity (~1 nJy), high spatial resolution (0.1 arcsec) observations. Deep, wide-field (1 deg^2) imaging of selected regions will provide the approximate distances, luminosities, and shapes of star-forming and quiescent galaxies to redshifts $z \sim 10$ (~95 percent of the way back to the Big Bang). Weak lensing and measurements of the internal dynamics of galaxies in these or similar data will provide the masses of galaxies by type and luminosity during the peak epoch of galaxy formation at epochs of $z = 1$–3.

Measuring the star formation rates, metal content, and clustering properties of early galaxies requires an extensive database of moderate resolution, near-infrared spectroscopy (R = 300–1000). Approximately 100,000 galaxies (z = 1–5) will be observed to determine accurately the evolution of galaxy luminosities and shapes over this epoch. SIRTF and an enhanced near-infrared camera on HST (WFC3–IR), as well as ground-based facilities, will contribute to this effort. However, the required combination of sensitivity, spatial resolution, and multiplexing (hundreds of spectra at one time) will not be achieved until the launch of NGST. NGST, with a mid-infrared instrument, and FAIR will be capable of detecting and studying completely dust-enshrouded star-forming galaxies at high redshifts ($1 < z < 10$).



Faint red objects detectable by the Near-Infrared Camera and Imaging Spectrograph (NICMOS) on HST may be newly formed, dust-enshrouded galaxies.



HST imaged the wind from a dying star, which enriches the galaxy with newly formed heavy elements.

OBJECTIVE 2 • Establish how the birth and aging of a galaxy influence the chemical composition that is available to stars, planets, and living organisms.

Our picture of the formation of the Solar System suggests that ices from the C-N-O family of elements and rocks made of Ca, Si, Mg, and Fe group elements are the raw materials for making planets. Life, at least as we know it, depends critically on the complex chemistry of organic matter — compounds built around carbon atoms. We have learned that these elements were first made in stars and are recycled into future generations of stars and potential planetary systems when the more massive stars explode as supernovae and less massive stars shed their metal-enriched envelopes through stellar winds. We believe that the gases containing these heavy elements remain gravitationally bound to the galaxies, slowly increasing their store of heavy elements over time.

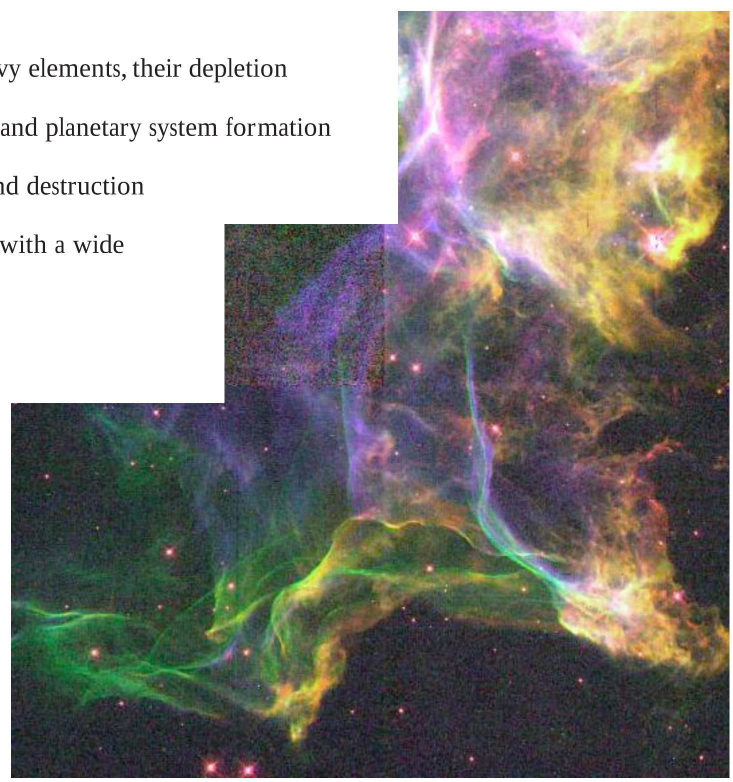
The understanding of how stars synthesize new elements is one of the great triumphs of science in the 20th century. However, we know relatively little of the overall enrichment process for interstellar gaseous material in the Universe. When and how did the process of chemical enrichment begin, and what kinds of influences regulated the process? Furthermore, we do not know the importance of heavy elements (in gas, molecules, and dust) for the formation of planets. For example, could very metal-poor stars, such as those in the most primeval globular clusters and in the Milky Way halo, have well-developed planetary systems? Do the complex hydrocarbons found in galactic clouds and star-forming regions survive to play a role in the formation of planets and their atmospheres? The answers to such questions will tell us whether the development of such giant, Milky Way–like systems is essential to the eventual emergence of life.

Wisps of gas from supernovae return heavy elements to the interstellar medium. Shown here is part of the Cygnus Loop.

INVESTIGATIONS FOR OBJECTIVE 2

Investigation 3: Trace the chemical evolution of the Universe from the birth of the first stars to the formation of dust, new generations of stars, and planetary systems.

A comprehensive understanding of the creation of heavy elements, their depletion onto dust grains, and the important role of dust in star and planetary system formation phenomena will require studies of 1) dust formation and destruction processes, 2) dust content and its properties in galaxies with a wide range of heavy-element abundances, and 3) star and planetary system formation phenomena in regions with high and low dust content. These investigations can be pursued by the direct observation of the dust through its thermal IR emission, as well as the extinction it produces against background sources; spectroscopy of the mid-infrared polycyclic aromatic



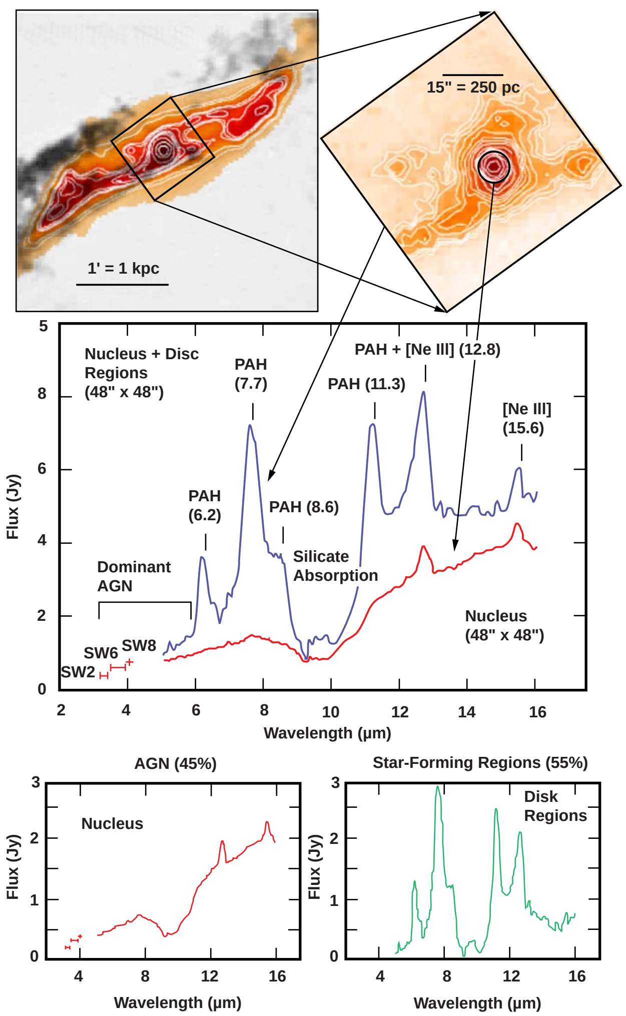
hydrocarbon (PAH) features; and the depletions of heavy elements derived from spectroscopic studies of the interstellar medium.

All elements heavier than boron are thought to be produced in the nuclear furnaces that power stars, or in supernovae, the explosive events that mark the end of heavier stars' lives. These explosions, along with the ejection of nova shells and the slow winds from evolved stars, send newly made heavy elements into the interstellar and intergalactic media. The creation and dispersal of these heavy elements can be measured by observing a number of key parameters. These parameters include the rates of supernovae (observable in the near-infrared to redshifts of $z > 7$), the strengths of spectral features around ancient star-forming regions, the integrated galactic light of established stars at redshifts $z > 2$, and abundances in the diffuse intergalactic medium. These measurements are made using a combination of ground-based telescopes and NGST (for $z > 2$) and HST/COS and SUVO for the $z < 2$ Universe. By comparing these data with the expected elemental yields from the stars producing the UV and far-infrared emission observed by NGST, FAIR, and ALMA to epochs beyond $z > 10$, we can construct a coherent and consistent picture of the formation and release of heavy elements in the Universe, as well as the differences in the abundances of metals from galaxy to galaxy.

The requirements for this portion of the investigation are similar to those needed to study the fate of baryonic matter (Objective 1). Sensitive spectroscopic measurements from the UV to the mid-infrared are essential. Sufficient photon flux to reach faint regions of star formation and the earliest supernovae (V ~ 27 mag, K ~ 25 mag) will require the large aperture of NGST coupled with state-of-the-art IR detectors. FAIR's great sensitivity and moderate angular resolution (~2 arcsec) in the mid- to far-infrared region are sufficient to determine the bolometric luminosity and implied heavy element production rate produced by forming massive stars at high redshift ($z \sim 1$-10).

Spectral resolution of R ~ 1000 in the IR is required to determine the chemical abundance of ionized, line-emitting gas in high-redshift star-forming galaxies ($z > 2$). Moderate-resolution UV spectroscopy of key diagnostic metal absorption lines using SUVO is needed to understand the dispersal and mixing of metals in the intergalactic medium by galactic winds near the peak epoch of star formation (z ~ 1-2).

FAIR is ideally suited to trace this chemical enrichment and evolution in detail through the history of the Universe from the Big Bang up to the present epoch. It will enable us to monitor the birth of the heavy elements carbon, nitrogen and oxygen, their incorporation into the first complex molecules and eventually dust particles, the raw materials needed for planet formation, and the emergence of life. Because 20 to 30 percent of the entire IR luminosity from the interstellar medium of many galaxies is emitted in a series of features characteristic of organic aromatic molecules, these provide an excellent tracer of carbon.



An infrared spectrum of the active galaxy Centaurus A from the Infrared Space Observatory (ISO) satellite shows strong emissions from heavy complex carbon molecules called PAHs.

Aromatic species are extremely stable hydro-carbons (similar to automobile soot and called PAHs), composed mainly of carbon atoms in hexagonal rings with a planar, chicken-wire-like structure. These are believed to be formed directly in the circumstellar shells of evolved stars, and thus their detection may be the best measure of the introduction of heavy elements into ancient interstellar media. In non-redshifted objects, most of this luminosity falls in a broad, intense band near 8 µm. In redshifted objects (z slightly > 2), this band shifts into the range available to FAIR. The sensitivity of FAIR will allow us to monitor the spectra of increasingly ancient objects all the way back to the Big Bang, revealing when these features first appear and revealing the structures of these carbon-rich molecules when they formed. Thus, by tracing these features, FAIR will determine the epoch of the first appearance of carbon in the history of the Universe. It was at this point in the history of the Universe, we believe, that Earth-like planets might have formed, ultimately leading to life.

Investigation 4: Determine when stars with planets could first have appeared in the Universe.

The heavy chemical elements such as C,N,O, Si, and Mg are the building blocks for planets and for life. What threshold abundance of these chemical elements is necessary to build planets and life? To answer this question, we need to search for planets around other stars over the full range of heavy element abundances. When the information is combined with the history of the chemical enrichment for galaxies like our own, we will learn when the potential for planets and life first appeared.

The requirements for conducting the key observations that are needed are high-spatial resolution, low-spectral resolution measurements at high sensitivity, and low background noise from the visible to the thermal IR. Large, ground-based telescopes like Keck, Gemini, and Magellan can be used to look for Jupiter-mass planets around the nearest low-metal-abundance stars at distances ~100 pc. Detection of Neptune-like or smaller companions around such stars will require yet more powerful, space-based instruments such as SIM and TPF. While Explorer-class missions might plausibly detect the presence of terrestrial-sized stellar companions within metal-poor globular clusters, only the LF mission will have the sensitivity to directly detect and study planets in old, metal-poor globular clusters at distances up to ~1000 pc.