Beyond JWST: The Next Steps in UV-Optical-NIR Space Astronomy

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1. Introduction

Over the course of two days, over a hundred astronomers from around the nation and the world met at the Space Telescope Science Institute to discuss future directions in UV-Optical-NIR astrophysics in the era beyond the James Webb Space Telescope (JWST). The program, list of participants, and videos and electronic versions of all the presentations and posters can be found at:

http://www.stsci.edu/institute/conference/beyondjwst

What emerged was an inspiring narrative of where modern astrophysics - enabled by new, forefront observations from space - can lead human discovery.

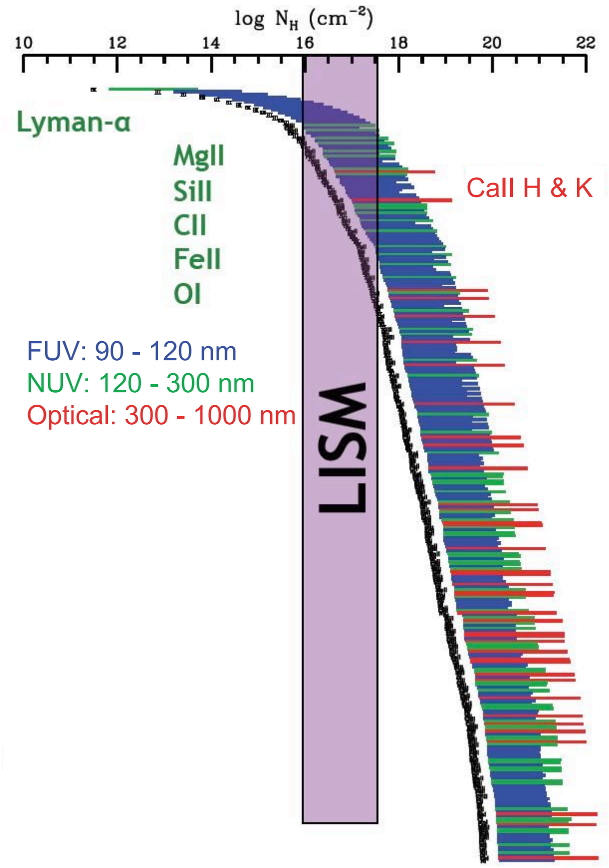
Space Science stands at an exciting and challenging threshold. Within the next two decades NASA could have the capabilities to search for life on exoplanets orbiting other stars and the tools to probe the complex processes that drive the evolution and structure of galaxies with unprecedented clarity. For the first time in human history, we have within our grasp the ability to unravel how, across the vast expanse of Cosmic time, our corner of the Universe became a safe harbor for the emergence of life. As profound, we may be able to answer the question "Are we alone?"

Observational astrophysics is a photon-limited field. The paradigm-shifting discoveries in the 2010 – 2030 era will require ever more capable instruments and facilities. In particular, for extrasolar planet characterization, as well as in the fields of star and galaxy formation and evolution, the next big steps require making observations at high angular resolution of sources with flux densities from a few to tens of nanoJanskys. The key photometric and spectroscopic signatures that will, for example, enable the search for life in the universe or provide the foundation for a comprehensive theory of star formation or enable *direct* measurements of interactions between galaxies and the cosmic web of matter lie in the wavelength range 0.1 – 2.5 microns.

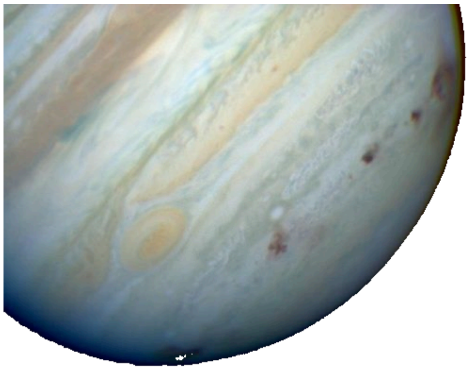
2. Science Opportunities

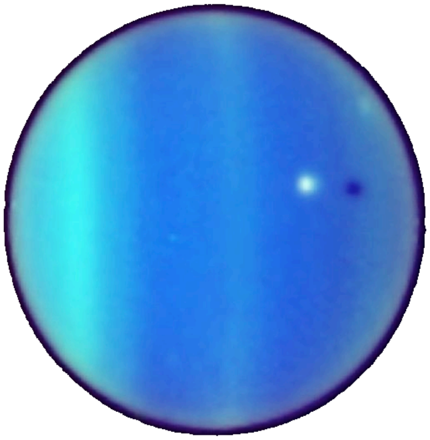
The ultraviolet, optical, and near infrared (UVOIR) regions of the electromagnetic spectrum are highly sensitive to many fundamental astrophysical processes. Hence, measurements at these wavelengths provide robust, and often unique, diagnostics of the roles of these processes in establishing a variety of astronomical environments and in controlling the evolution of a variety of objects. Our knowledge of star formation and evolution, of the growth of structure in the universe, of the physics of jet phenomena on many scales, of the nature of active galactic nuclei and supermassive black holes, of aurora on and atmospheric composition of the gas giant planets, and of the physics of protoplanetary disks has either been gleaned or greatly expanded through UVOIR observations.

We summarize here the compelling and broad science, presented at the “Beyond JWST” workshop, that can be done with future UVOIR space astronomy missions in the next 25 years. Most of these astronomical investigations require major increases in angular resolution, image contrast ratio, and/or sensitivity over those expected from existing or planned facilities in the 0.1 to 2.5 micron wavelength range.



The power of UV spectral diagnostics is shown in this diagram by Seth Redfield. In the study of the local interstellar medium (LISM) all but two of the key diagnostic lines are in the UV.





2.1 The Solar System

Exploration of our Solar System is in a Golden Age. Planetary orbiters, fly-bys, and landers have brought spectacular and historic discoveries. But there is still a lot to learn:

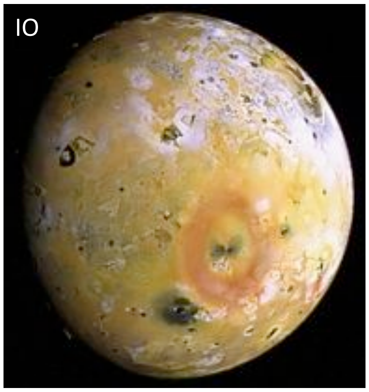
HOW AND WHY DO PLANETARY SYSTEMS FORM?
HOW DO PLANETS EVOLVE INTO HABITABLE WORLDS?
WHAT IS THE HISTORY OF LIFE IN THE SOLAR SYSTEM?

Our Solar System provides many “laboratories” where we can search for the answers to these questions in unprecedented detail.

Yet much of planetary science relies on remote sensing with telescopes on, and in orbit about, the Earth. This will continue to be true in the coming decades.

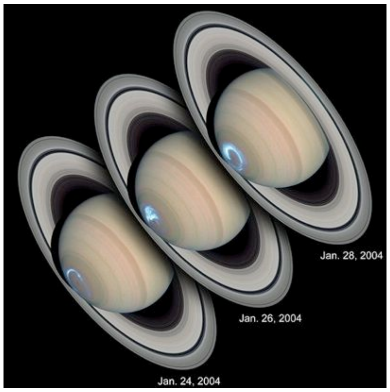
Representative Observations: Understanding Planetary Atmospheres

EUROPA: Auroral emissions from Europa's tenuous O_2 atmosphere were first detected by HST in the Ultraviolet (135.6 nm) with limited S/N and spatial resolution (Hall et al. 1995). Its heterogeneous distribution suggests a complex atmosphere. Does Enceladus-like venting contribute to the peculiar spatial distribution? Similar or better observations will provide valuable support for the NASA Europa Mission in the 2020s by assisting in the search for endogenic activity.



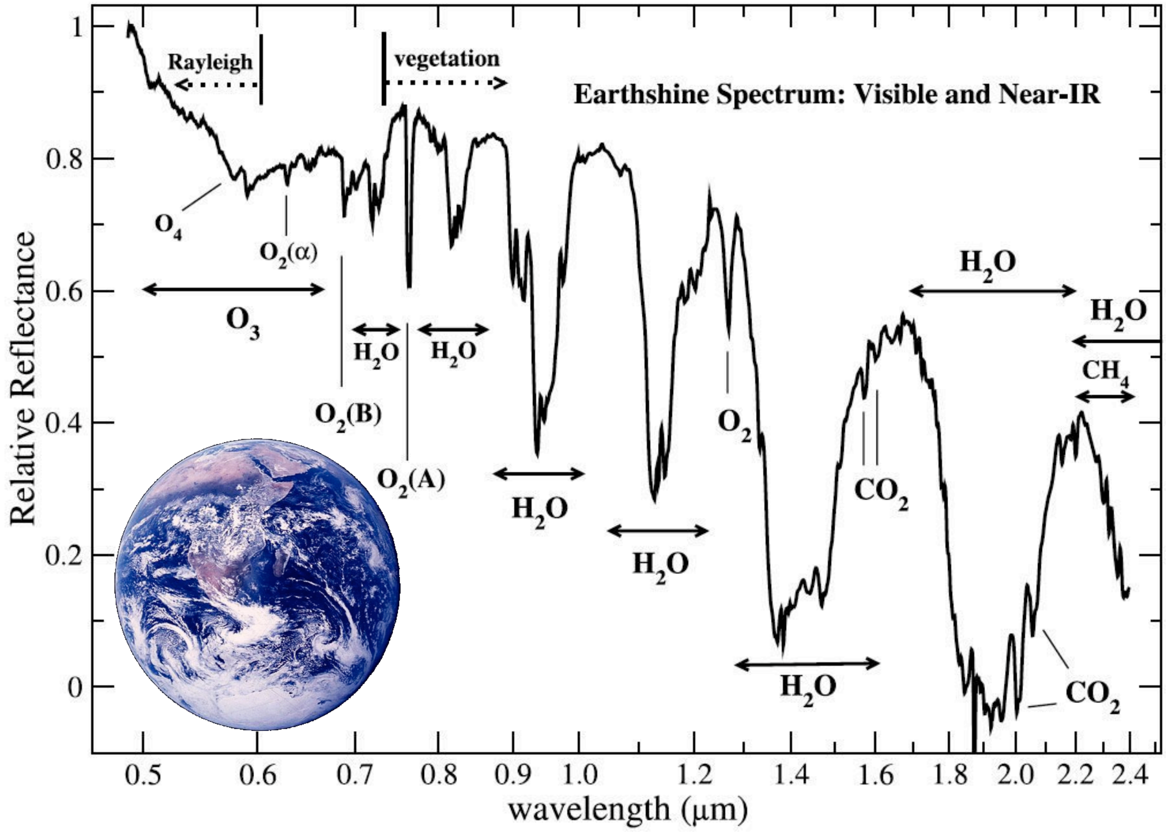
PLUTO: CH_4, N_2, and CO are currently detected or inferred in Pluto's thin atmosphere. Models predict C_4H_2, C_6H_2, HC_3N, and C_4N. Their abundances strongly constrain photochemical processes. But these species will not be detectable by the New Horizons spacecraft. The presence of these molecules in Pluto's tenuous atmosphere are detectable with a spectrograph capable of sensitive observations in the mid-UV. HST sensitivity is marginal.

IO: Io has a complex and variable SO_2 atmosphere. It is observable via strong absorptions in mid-UV and Ly-alpha, and emission features in FUV. Spatially-resolved mapping of the full disk at multiple epochs is possible but HST's sensitivity is marginal, making it inefficient. Improved UV sensitivity will greatly improve our understanding of Io's complex interaction with the Jovian magnetosphere.



GIANT PLANET AURORAE: Combined HST and Cassini observations are very effective in revealing physics behind Saturn's aurora. UV imaging and spectroscopy of aurora in outer gas giants is essential for tracking the influence of solar wind across the Solar system. To further our understanding of the influence of the solar wind on the outer Solar system we will need UV imaging and spectroscopic capabilities into the 2020 decade.

2.2 The Search for Life in the Galaxy



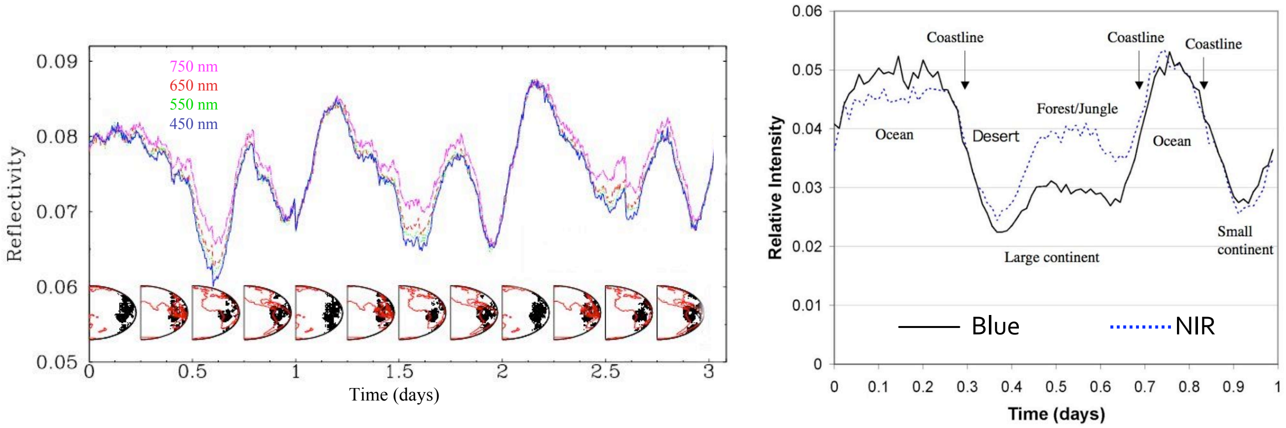
Above: Absorption features from O_3, O_2, H_2O dominate the reflected visible and Near-IR spectrum of Earth (Turnbull et al. 2006). These signatures readily distinguish the Earth from the other planets in the Solar system as a site where biological activity is occurring.

> "Four hundred years after Galileo's discoveries via the first astronomical use of the telescope, the world's astronomers are once again using powerful new instrumentation to make startling discoveries of and about new planets, quite literally other worlds, which promise to once again transform our understanding of the nature of the Earth and of life's and humanity's places in the cosmos."
>
> - Ed Turner, March 2009

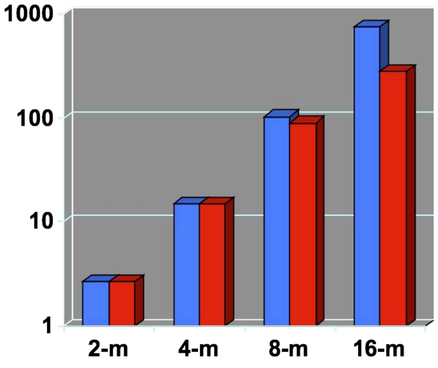
Representative Observations:

Characterizing Exosolar Terrestrial Planets

If one can sufficiently suppress the light from the star about which an exoplanet orbits, then optical and NIR broadband photometry and low-resolution spectroscopy can reveal much information about the planet's atmospheric composition, habitability, surface geography, potential biological activity, rotation period, and weather patterns.



Above (Left): Model of the variation in the broadband optical (BVRI) reflectivity as a function of time for Earth (Ford et al. 2003). Variations of up to 30% are due to changes in albedo as the planet rotates, putting different mixtures of land and sea into the observer's line of sight. Above (Right): Variations in the intensity of polarized visible and NIR light.



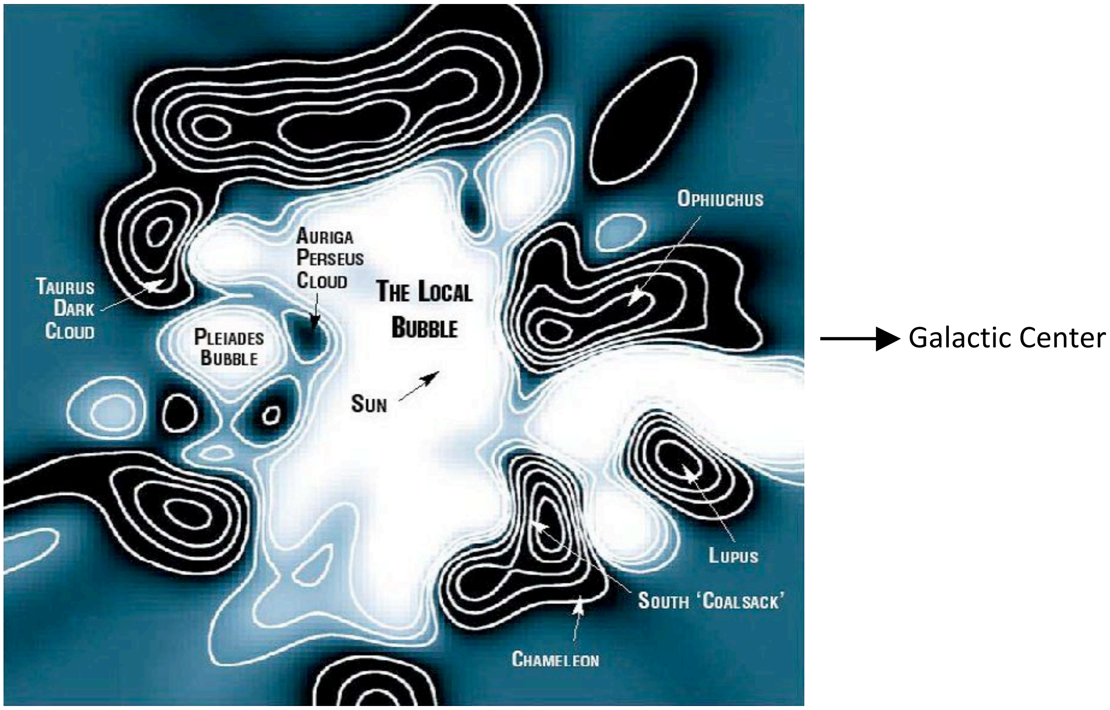
Blue bars show the total number of F,G,K stars for which SNR=10, R=70 spectrum of Earth-twin could be obtained in <500 ksec **as a function of space telescope aperture**. To derive the number of life-bearing planets that might be detected, **one must multiply these numbers by fraction of stars that have an Earth-like planet, with detectable biosignatures, in the Habitable Zone.**

Red bars show the number of F,G,K stars that could be observed 3x each in a 5-year mission without exceeding 20% of total observing time available to community.

ARE THERE OTHER WORLDS WHICH RESEMBLE THE EARTH?
IF SO, HOW COMMON ARE THEY?
HOW ARE THEY SIMILAR? HOW ARE THEY DIFFERENT?
ARE ANY OF THEM LIFE-BEARING?
IF SO, WHAT FORMS DOES ALIEN LIFE TAKE?

2.3 The Local Interstellar Medium

The region of space within 250 pc of the Sun is a rich environment. It contains ~10 million stars, hundreds of known exoplanets, a broad range of interstellar gas phases from very low (20 K) to very high (10^7 K) temperatures, several star forming regions and dozens of resolved stellar debris disks.



Lallement et al. 2003

Key directions for future ISM and stellar research include:

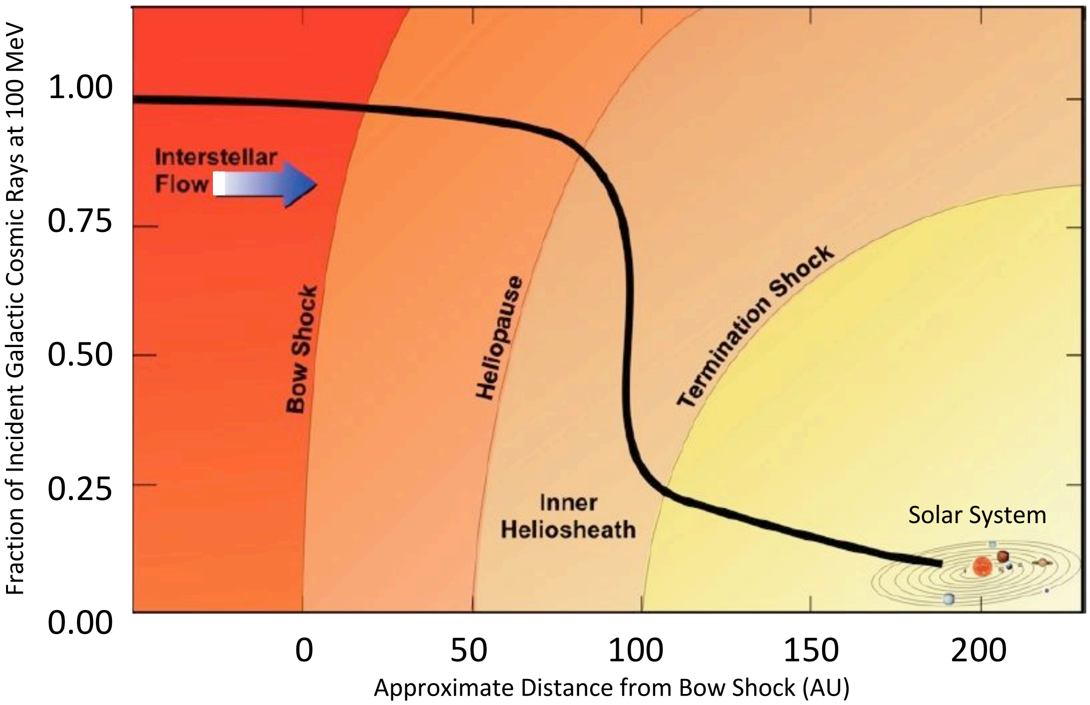
HOW DO STARS AND THEIR PLANETS INTERACT WITH THE INTERSTELLAR MEDIUM THAT SURROUNDS THEM?

HOW DOES THE LOCAL INTERSTELLAR MEDIUM MODULATE COSMIC RAY FLUX?

HOW DOES STELLAR ACTIVITY ALTER HABITABILITY AND LIFE?

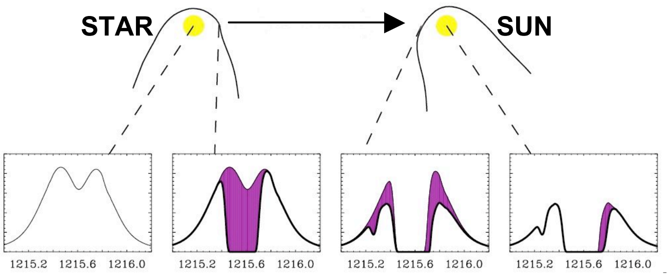
Representative Observations:

Heliopause and Exo-heliospheres



The Heliosphere is defined by the LISM properties (e.g., plasma temperatures, HI gas densities). The LISM modulates galactic cosmic ray (CR) flux on solar system bodies. The CR flux can influence cloud cover, lightning intensity, and surface mutation rates. The CR flux can also alter ozone and methane biomarker strength on fairly short timescales. The structure of the heliosphere is easily altered by ISM-induced compression.

Better understanding of the interaction between the ISM and exo-heliospheres (astrospheres) is an important focus for future studies. It will help us understand the role the ISM plays in affecting the Habitable Zones around stars. ***Astrosphere structure can be determined from very high resolution Ly-alpha absorption spectroscopy.*** Such observations allow us to study both the structure of the astrospheres around nearby stars and our local heliosphere.



Excess UV Ly-alpha absorption due to the hydrogen "walls" from both our heliosphere and the astrosphere of a nearby star encodes information on the properties of the stellar wind, magnetic field, and exoplanetary cosmic ray field (Wood 2004).

2.4 The Assembly of Galaxies

Resolved stellar populations are cosmic clocks that can be used to trace the evolution of chemical abundance, stellar mass, and kinematics as functions of time and position within a galaxy. This information provides critical verification of and constraints on models for both star and galaxy formation.

The key questions that can uniquely be addressed through the study of resolved stellar populations in both the Milky Way and other galaxies are:

WHAT IS THE FORMATION TIME AND ASSEMBLY HISTORY OF GALAXIES?

HOW MUCH ENERGY IS INPUT INTO THE ISM FROM STELLAR BIRTH AND DEATH?

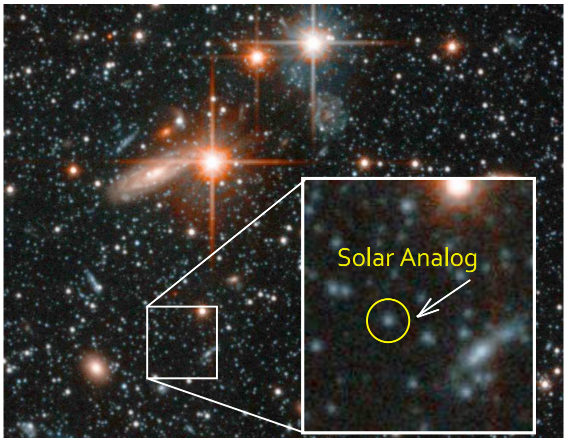
DOES THE INITIAL DISTRIBUTION OF STELLAR MASSES DEPEND ON ENVIRONMENT?

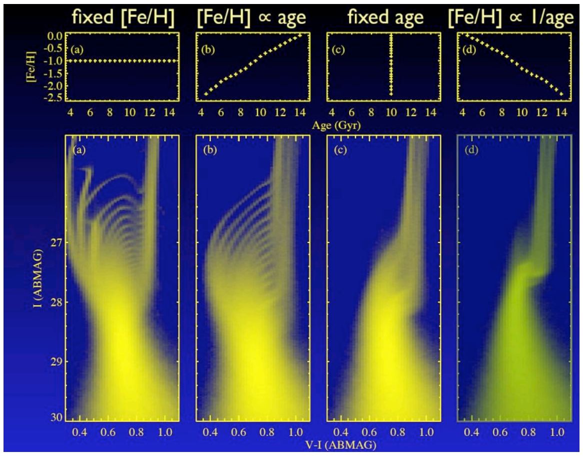
WHAT ARE THE MASSES OF UNDETECTED TRANSIENT PRECURSORS?

Representative Observations:

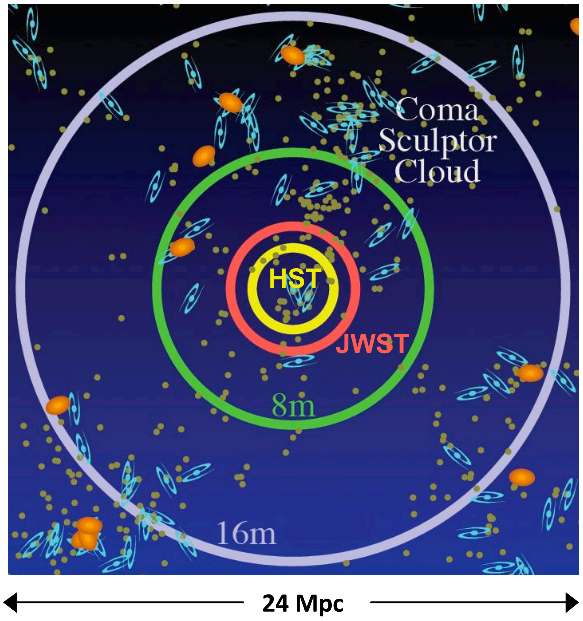
Star formation histories beyond the Local Group

The accuracy with which a spatially resolved star formation history (SFH) can be reconstructed depends critically on how many phases of stellar evolution can be detected. ***The most accurate reconstructions require detection of individual stars on the giant branch as well as individual dwarf stars, like the Sun, near the turn-off of the main sequence. Figure to the right shows a solar analog star in M31***.





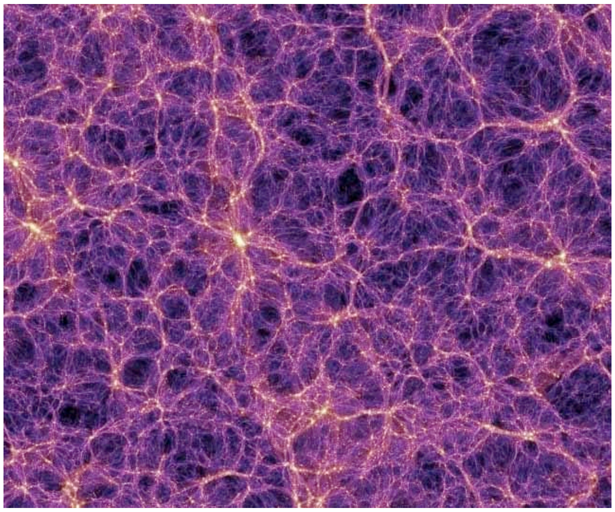
If both blue and far-red broadband photometry are available to measure the stellar color-magnitude relation (see figure to left), the degeneracy between metal abundance and age can be broken, enabling an accurate SFH to be measured and enabling individual components of a galaxy to be "tagged" by age and metallicity.

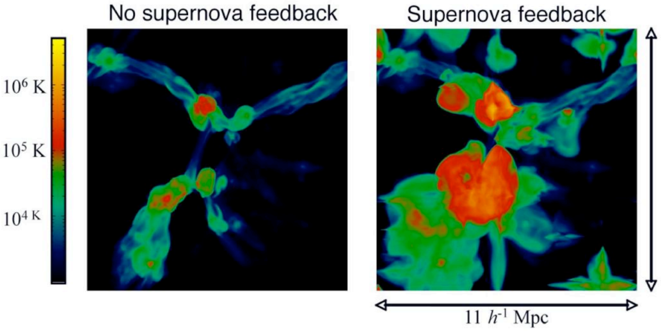


To perform such observations beyond the Local Group - essential for accessing the full range of star forming environments - ***one needs a large UV-Optical space telescope.*** The circles show the distance out to which a space telescope of the indicated aperture can obtain SNR=5 V & I band photometry down to solar analog stars in 100 hours of exposure time.

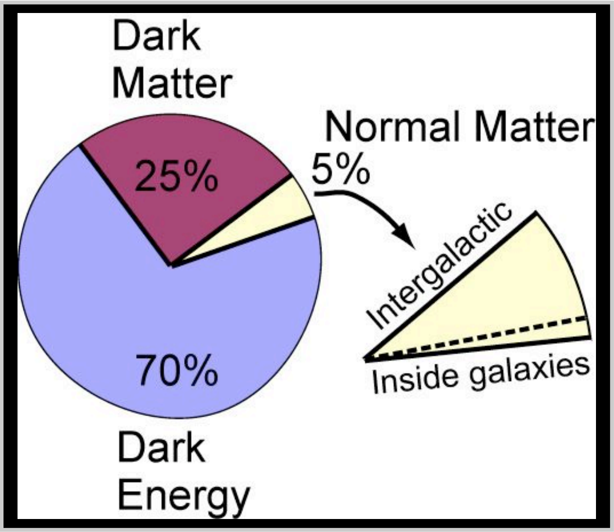
2.5 The Cosmic Web

Most of the matter in the Universe is located in intergalactic space outside of galaxies. Understanding how gas in the intergalactic medium (IGM) gets into galaxies and how galaxies respond to inflow lies at the heart of understanding galactic evolution. Depending on the mass of the galaxy halo, infalling gas may be shocked and heated or accrete in cold mode along narrow filaments. Gas can also be *removed* from galaxies via tidal and ram pressure stripping, or during the accretion of gas-rich dwarfs onto giant galaxies.





IGM gas temperature distribution for cosmological models with and without supernova feedback (Cen & Ostriker 2006).



Metal-enriched gas introduced into the IGM by these processes will be dynamically cool. All of these accretion and gas removal theories have observational consequences (see the figure at bottom left) that can be tested if the distribution of gas in the cosmic web around galaxies can be characterized through UV absorption and emission line spectroscopy. The key questions are:

HOW IS INTERGALACTIC MATTER ASSEMBLED INTO GALAXIES?

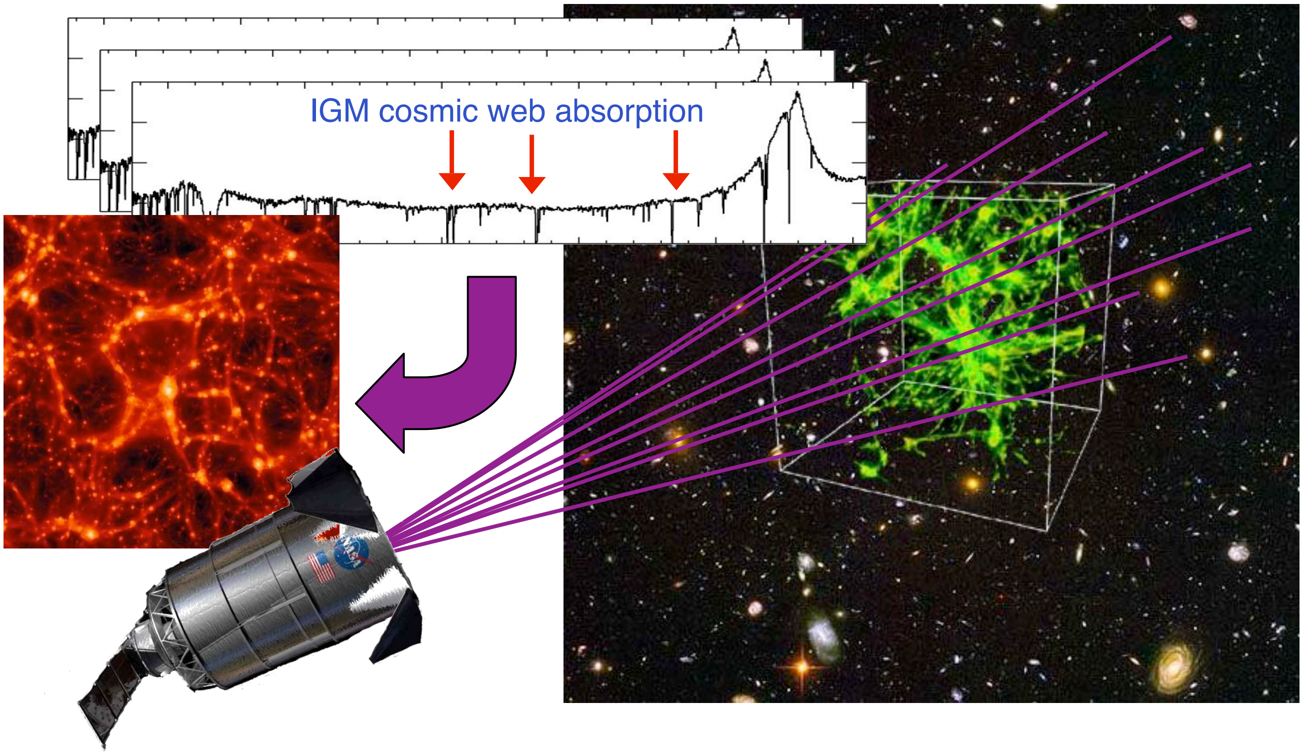
TO WHAT DEGREE DOES GALAXY FEEDBACK REGULATE AND ENRICH THE IGM?

WHERE AND WHEN DO THESE PROCESSES OCCUR AS A FUNCTION OF TIME?

Representative Observations: Mapping the IGM-Galaxy Interface

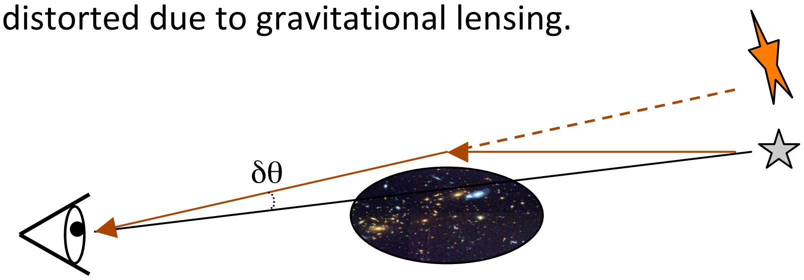
The observational challenge is to probe a suitably large number of background sources and with enough diagnostic power (i.e., spectral resolution) to identify and characterize the processes at work at the IGM - galaxy interface (regions within a few hundred kpc of a galaxy). Dramatically increased absorption line sensitivity at UV and optical wavelengths is crucial for reaching the required background source densities. There are ~100 quasars per square degree that are brighter than a *GALEX* FUV flux of 24th magnitude. ***At this sampling density, one can select sight lines next to thousands of examples of any common galaxy, group, or cluster, yielding a high-resolution map of the gas and metals surrounding these structures.*** One will also want to systematically target individual nearby galactic coronae and groups of galaxies, for which it would be possible to observe the production sites of heavy elements (star-forming regions, SNe, emission nebulae), follow the processes by which the elements are transported within galaxies, and trace the expulsion of metals into the IGM.

With space telescopes in excess of 8-meter apertures, one could also use multiple quasars *and* distant galaxies as background continuum sources to dissect the gas distribution in fields known to have galaxies and gas at the same redshift.



2.6 Gravitational Lensing

The images of galaxies lying behind foreground galaxies and clusters of galaxies can be significantly distorted due to gravitational lensing.

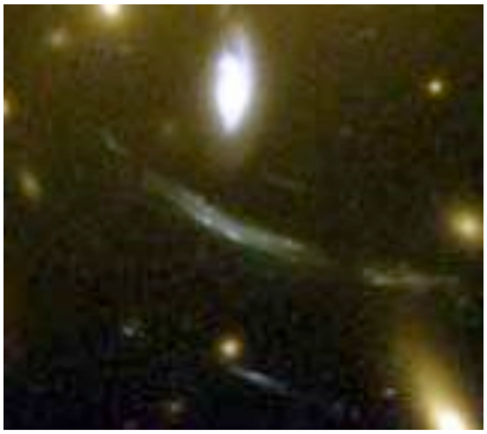


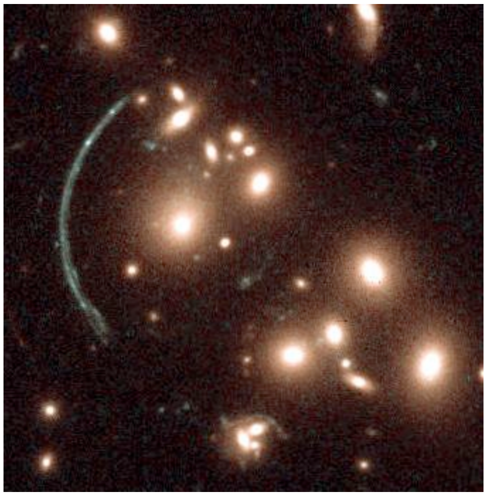
The amplitude of the distortion, and the number of "multiple images" of a background source produced, ***provide fundamental constraints on the distribution of matter in the foreground objects.*** This, in turn, allows the mass profile of the foreground "lensing" object to be derived with unprecedented accuracy. In the case of strong lensing, usually seen in the direction of massive galaxy clusters, the lensing signatures also ***provide unique constraints on cosmological parameters and on the structure of very distant background galaxies***. The highly stable, diffraction-limited imaging that an optical space-based telescope provides on moderately wide angles (3 - 10 arc minutes) enables us to address these key questions:

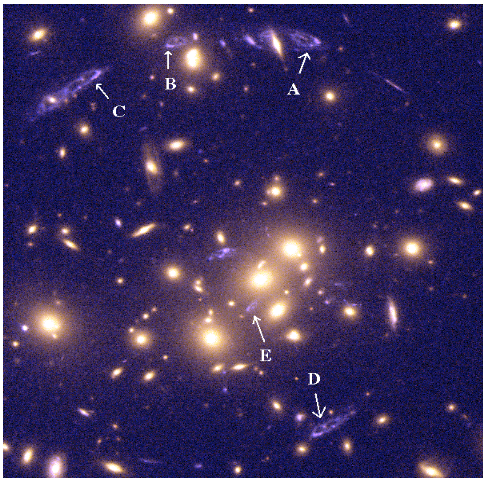
HOW IS DARK MATTER DISTRIBUTED ON SCALES OF 10 KPC TO 5 MPC?

WHAT IS THE LINK BETWEEN X-RAY GAS AND DARK MATTER?

WHAT IS THE DISTRIBUTION OF DARK MATTER HALO MASSES AND RADII?

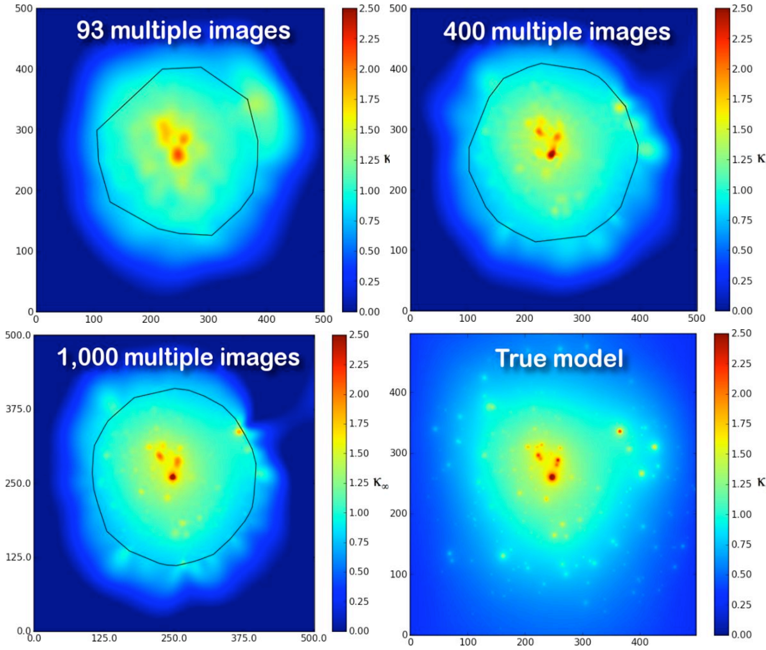






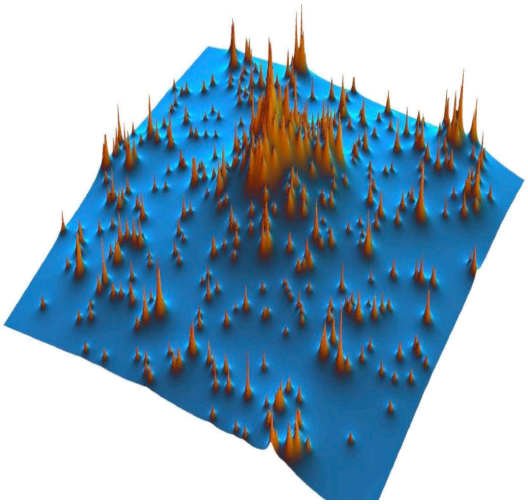
Representative Observations:
Precision Substructure Mapping

There are two key science goals from detected strong lensing in clusters: (i) substructure mapping and (ii) constraints on dark energy from multiple sets of multiple images. For both these applications, high angular resolution is key as the accuracy of the derived substructure map and the constraints on dark energy both scale (non-linearly) with the number of multiply-imaged systems that can be detected (as shown in the figure below from Coe 2009).



While adaptive optics systems on large ground-based telescopes will likely produce intermediate Strehl ratios in the NIR over 1 or 2 arc minutes, one requires very stable, ~10 milli-arcsec point spread functions on scales of 5 - 10 arc minutes from a space-based optical telescope to make ***the next major leap in studying sub-galactic scale structure: detection of hundreds of multiple images of background galaxies.***

The deep HST/ACS image of Abell 1689 has about 100 sets of multiple images. This yields a mass map that has a resolution of 0.6 arcsec, which translates to a lower mass limit on the detected sub halos of 2 x 10^{11} M_{SUN}. The next frontier requires us to improve this limit downwards by at least one order of magnitude (to see if there is a substructure "crisis" in LDCM on cluster scales). This requires detecting ~1,000 sets of multiple images. ***Such capability requires a five to tenfold improvement in angular resolution in the optical band over that available with HST.***



Mass map of cluster CL0024+16 at z = 0.40 based on a sparse-sampled survey using WFPC2 on the Hubble Space Telescope (Treu et al. 2003).

3. Requirements & Technologies

for future UVOIR space astronomy missions

The table below summarizes the range of high-level scientific requirements that we will need to address the many fundamental questions identified during the course of the workshop. ***A consensus appeared to emerge amongst the workshop participants*** for a) continued access to UV wavelengths, b) high angular resolution coupled with high-spectral resolution in the UV, c) moderately wide-field (4 - 8 arc minutes), high angular resolution imaging over the full UVOIR wavelength window with a very stable point spread function, d) high-contrast (10^{-10}) optical and NIR imaging to within ~50 mas of nearby stars to conduct direct detection and characterization of exoplanets.

Science Case	**Field of View**	**Wavelength Coverage (microns)**	**Sensitivity**	**Angular Resol.**	**Spectral Resol. (R=$\lambda/\Delta\lambda$)**	**Technologies**
Atmospheric chemistry & dynamics of outer solar system bodies	50"	0.11 - 2.40	SNR=20 - 50 at R=10^4 in FUV for 20 AB mag	<0.02"	Up to R=10,000 adequate R=30,000 desired	High-efficiency solar blind detectors, large aperture UV optics
Characterization of Earth-mass exoplanets in Habitable Zone	<10"	0.65 - 1.10 adequate 0.30 - 2.40 desired	SNR=10 at R=70 for V=30 point source	<0.03"	R=5 to R=100	Very high-contrast coronagraph or external occulter, stable wavefront control with large aperture, photon counting detectors
Properties of Local interstellar medium and astrospheres	<20"	0.11 - 0.90 adequate 0.10 - 1.70 desired	Need high dynamic range plus SNR=100 for R=10^5, V=14	~0.1"	Up to R=150,000	High-efficiency UV detectors and coatings, high resolution spectrograph
Star formation in the full range of galactic environments	4 - 8 arcmin	0.35 - 1.00 adequate 0.11 - 1.70 desired	SNR=5 for broadband imaging of V=35 point source	<0.016"	R=5 for imaging	Large-aperture space telescope that is diffraction limited at 0.5 microns
The role of the IGM in galaxy evolution	1 - 2 arcmin	0.10 - 0.30 adequate, 0.10 - 1.20 desired	SNR=10 at R=20,000 in FUV, 24 AB mag source	0.01" - 0.10"	R=20,000 to 50,000	High-efficiency UV detectors & coatings, photon counting detectors

4. Summary

UVOIR astronomy has a promising future if astronomers think boldly about where the next frontiers lie in this rich field. The most exciting of these frontiers involve resolving sources on or below angular scales of 20 milli-arcseconds, obtaining very high resolution UV and blue-optical spectra on similarly small angular scales, and obtaining photometry and modest resolution spectroscopy of nano-Jansky sources at signal-to-noise ratios of 5 to 10 across the 0.1–2.5 micron wavelength range.

Many of these challenging requirements demand large apertures in space - apertures of at least 8 meters in diameter and, by the end of 2020 decade, up to 20 meters. Incremental progress in telescope aperture are not compelling, so radical advance is needed. Fortunately, the technology needs of several communities are aligning to make large space-based optical systems affordable.

As we have seen with the Hubble, Chandra, and Spitzer Space Telescopes, NASA's Great Observatories have the ability to deliver much more than unique forefront science to a broad community of scientists. They also have the demonstrated capability to captivate the public and inspire school children across this Nation. Our community, in partnership with NASA and industry, once again needs to step up to the challenge of inspiring the Nation as we seek to understand the origins of life and the cosmos.

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