Making the Most of the Great Observatories: Cosmology and Large Scale Structure

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- The Value of $H_0$
- Cosmic Acceleration
- The Extragalactic Background Light
- The Low Redshift Baryon Census
- Dark Matter and Galaxies
- The Physics of Galaxy Formation

The Value of $H_0$

A key cosmological parameter

Recent cosmological developments make a precise measurement of $H_0$ more interesting, but raise the stakes.

HST Contribution: Key Project determination to 10%

Freedman et al. 2001

![Direct Cepheid distances](image1)

![Calibrated secondary distances](image2)
The Value of $H_0$
A key cosmological parameter

Recent cosmological developments make a precise measurement of $H_0$ more interesting, but raise the stakes.

HST Contribution: Key Project determination to 10%
BUT: LMC calibration remains a significant hole

LMC Distance: 48.8 ± 3.6 kpc, $H_0 = 74 ± 7$ km s$^{-1}$ Mpc$^{-1}$
L. Macri et al. 2006
The Value of $H_0$

Observational Goals:
- Test LMC distance scale, e.g., maser galaxies
- Robustly improving precision to 5% ($2\sigma$, statistical + systematic) would be of great value.

Coma Cepheids? Golden Lenses?
1% distance measurement to Andromeda using time variable dust scattering echoes of AGN (10 Msec Chandra project)?

Standard of Merit: If direct $H_0$ measurements disagree with standard model inference from CMB + LSS at $3\sigma$, will we believe the former?

Cosmic Acceleration
The biggest cosmological mystery today

Conservatively: A new and dominant cosmic component with bizarre physical properties.

Less conservatively: A signature of the breakdown of GR, extra dimensions, observable consequences of string theory, …
HST Contributions:
• Post-SN images of high-z hosts, enabling good photometry of SN discovered in ground-based surveys.
• Light curves of some ground-based SN detections.
• Discovery and light curves of supernovae at $z > 1$, deceleration epoch.

Riess et al. 2004

Cosmic Acceleration

$$H(z) = H_0 \left[ \Omega_m (1+z)^3 + \Omega_k (1+z)^2 + \Omega_{DE} (1+z)^{3(1+w)} \right]^{1/2}$$

$$d_L(z) = c (1+z) \int_0^z \frac{dz'}{H(z')}$$

Current focus: What is $w$? $[\rho_{DE} = \rho_{DE,0} (1+z)^3 (1+w)]$

Observational Goals:
• Test systematic uncertainties.
• Maximize precision on $w$ (and $\Omega_{DE}$).
• Lay groundwork for JDEM (supernovae and weak lensing).
Mostly Useful Supernova Telescope For our Later Years (A. Fruchter)
Cosmic Acceleration
Observational Programs:

• Continuing support for ground-based SN searches as needed.
• Weak lensing calibration of cluster mass indicators.
• Cosmic shear measurements of clustering evolution.

Standard of merit: Improve precision on or test systematics of $w$ measurements, competitively with ground-based experiments. Test JDEM methods/limitations.

Should HST carry out more supernova searches?
Motivation: detect time variation of $w$, high-z needed.

$$H(z) = H_0 \left[ \Omega_m (1+z)^3 + \Omega_k (1+z)^2 + \Omega_{DE} (1+z)^{3(1+w)} \right]^{1/2}$$
Distinguishing time varying $w$ from closest constant $w$ model is very hard, even for maximally optimistic assumption about time variation.

Cosmic Acceleration

Observational Programs:

• Continuing support for ground-based SN searches as needed.
• Weak lensing calibration of cluster mass indicators.
• Cosmic shear measurements of clustering evolution.

Standard of merit: Improve precision on or test systematics of $w$ measurements. Test JDEM methods/limitations.

Should HST carry out more supernova searches?

Minimal standard of merit: For most optimistic assumption about time variation, expect $3\sigma$ discrimination from closest constant $w$ model.
The Extragalactic Background Light
Fossil record of star formation and black hole accretion
Potential testing ground of new physics

Fardal et al. 2006

HST Contribution:
resolved galaxy contribution, absolute measurement (factor 2-4 difference)

Spitzer Contribution:
resolved source contribution at 24µ, 70µ, 160µ, absolute (fluctuation based) measurement in near-IR

Chandra Contribution:
resolved 0.5-10 keV background into sources (resolved and absolute measurements agree)
Estimates of EBL and local K-band light density (~local stellar mass density) conflict, given observed star formation history and standard IMF.

The Extragalactic Background Light

Observational goals:
- Close gap between resolved sources and absolute measurements.
  - Raise lower limits from resolved sources.
  - New absolute measurements.

Standard of Merit: Any significant improvement valuable.
The Low Redshift Baryon Census
Basic Bookkeeping

BBN and CMB: $\Omega_b \approx 0.022h^2 \approx 0.05$
At $z\sim3$: most baryons are “detected” in the Lya forest.
At $z=0$, about 10% in galaxies, 10-20% in detected X-ray emitting gas.

Most low-z baryons are “missing”.
Theory predicts: At low $z$, most baryons are in a thin Lya forest or a relatively diffuse, shock heated medium (a.k.a. “WHIM”).
HST Contributions:

- Absorption Line Key Project:
  Low-z Lyα forest is thin, but thicker than power-law extrapolation from high-z

- STIS programs:
  Statistics of low column density systems, the true analogs of the typical high-z forest. Relation between absorbers and galaxies/large scale structure.

Weymann et al. 1998

Davé et al. 1999

Penton, Stocke, & Shull 2002
The Low Redshift Baryon Census

HST Contribution (also FUSE):

- Detailed characterization of low-z Lyα forest and correlation with galaxies
- Detection of low-z OVI absorbers that probably represent the cool end of the WHIM

Tripp, Savage, & Jenkins 2000

Fang & Bryan 2001
At typical WHIM temperatures, dominant ionization stages of oxygen should be OVII, OVIII. “X-ray forest.”

For IGM oxygen abundance = 0.1 solar

The Low Redshift Baryon Census

Chandra Contribution:

• Absorption at $z \approx 0$, OVII, OVIII, NeIX, NeX, CVI: Clear detections but unclear interpretation -- nearby, Extended Halo, or Local Group?
• Intervening absorbers: one 3.8σ detection at $z=0.011$, multiple weaker or ambiguous detections, several sightlines

Chen et al. 2003
Mrk 421 Sightline

Nicastro et al. 2005

The Low Redshift Baryon Census

Observational Goals:
• Probe low column density Lya forest at low z.
• Fully characterize relation between Lya forest and galaxies.
• Map shock-heated IGM as well as possible.
The Low Redshift Baryon Census
Observational Programs:
• Cosmic Origins Spectrograph tremendously powerful instrument for low-z Lyα forest and low-z OVI absorbers.
• Sensitive X-ray emission measurements extending beyond virial radii of clusters and groups.
• X-ray absorption measurements with Chandra are hard, but may be the only chance of characterizing main body of WHIM until Constellation-X.
  • 1.4 Msec spectrum of z=0.36 blazar “should” yield 10-20 lines, OVII/OVIII and CV (Nicastro et al. poster).
  • OVI matching reduces contamination but may miss strongest OVII absorbers.

Standard of Merit: Significantly improve empirical understanding of low-z baryon distribution and relation between IGM and galaxies.

COS also very powerful for probing HeII forest at high redshift.
Trace process of helium reionization.
Major cosmic phase transition, with significant implications for Lyα forest and its cosmological applications.

Q1157+1343, z=3, HST/STIS, Reimers et al. 2005

HS 1700+6416, z=2.72, FUSE, Fechner et al. 2006
Dark Matter and Galaxies
From the seen to the unseen

Basic Questions:
• What is the relation between galaxies and dark matter, over a wide range of lengthscales and redshifts?
• How does the clustering of dark matter change with time?

Koopmans et al. 2006
Elliptical galaxies have approximately flat circular velocity profiles.
Flux ratio anomalies reveal small scale structure in lensing potential.

Sometimes micro-lensing (1 Msun scale), sometimes milli-lensing (10⁶ Msun scale).

- Cluster cores are dense.
- Galaxies in clusters have halos; collisional dark matter disfavored.
- Galaxy halos in clusters are tidally truncated.
SDSS: Galaxy correlation function deviates from a power-law.

Explained by halo occupation model. Matching observed galaxy clustering constrains relation between galaxies and dark matter halos.
Lee et al. 2006

Method applied to GOODS galaxies at $z \sim 3, 4, 5$

Conroy, Wechsler, & Kravtsov 2006

DEEP2, $z \sim 1$  GOODS, $z \sim 4, 5$  Subaru, $z \sim 4$

Assuming monotonic relation between galaxy luminosity and dark matter subhalo mass gives zero-parameter match to observed correlation functions over wide range of redshifts and luminosities.
Dark Matter and Galaxies

Lensing (strong and weak):
- Elliptical galaxies have approximately flat circular velocity profiles.
- Galaxy halos have substantial ~10^6 M sun substructure.
- Cluster cores are dense. Galaxies in clusters have halos; collisional dark matter disfavored. Galaxy halos in clusters are tidally truncated.
- Measurements of galaxy-mass and mass-mass correlation functions from ~100 kpc to ~10 Mpc scales.

Clustering:
- Constraints on relation between halo mass and galaxy number.
- Relatively simple models explain broad sweep and subtle features of data.

Dark Matter and Galaxies

Observational Goals:
- Better constraints on galaxy mass profiles, substructure
- Constrain halo occupations via clustering for galaxy classes defined by mass, SED, morphology, over range of redshifts
- Measure galaxy-mass and mass-mass correlations
- Lay ground-work for future wide-field imager (MUSTFLY)

Observational Programs:
- High resolution imaging of strong lenses (also multi-wavelength imaging of AGN aceretion disks via microlensing)
- Large surveys, multi-wavelength, deep in at least one band (Is there more to do, or are surveys to date adequate?)
The Physics of Galaxy Formation

Distribution of galaxy star formation histories is bimodal.

The most massive galaxies are red.

Bimodality already in place by $z=1$.

Red sequence grows from $z=1$ to $z=0$.

Bell et al. 2004, COMBO-17

Key Questions:

• What causes bimodality of the galaxy population?
• What shapes the galaxy luminosity function?
• What determines galaxy morphology?
• What is the link between galaxies and their central black holes?
• Is the stellar IMF universal?
In hydrodynamic simulations, low mass galaxies accrete gas from cold, filamentary streams. High mass galaxies accrete gas from hot, diffuse halos.

If AGN feedback suppresses hot accretion:
- sharp cutoff in $\Phi(L)$
- Massive galaxies are red
- Massive galaxies formed by mergers

Does this happen on individual galaxy scales?
The Physics of Galaxy Formation

Observational Programs:
• Map Φ(M*, SED, morphology, environment, redshift) as fully as possible. (Done?)
• Measure Extragalactic Background Light and understand its sources.
• Characterize AGN hosts over wide range of z, L, SED.

Top Priorities for the Great Observatories?
• Attain convincing 5% limits on $H_0$ (95% confidence, statistical and systematic).
• Convincingly pin down the EBL and its sources.
• Map the diffuse low-z IGM as thoroughly as practical.

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