Latest Results from Multi-wavelength Galaxy Surveys

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Galaxy Surveys

• The aim is to study nature of different populations of galaxies in the nearby, or distant universe and explore properties of galaxies as a function of look-back time

• A galaxy survey would reveal:
  – the frequency of galaxies as a function of their
    • Luminosity
    • Structure (Size, bulge-to-disc ratio, etc..)
    • Dynamical mass
    • Star formation rate
    • Color (or spectral energy distribution) of the stellar population
  – The connection of individual galaxy properties with their “environment” (e.g. cluster or field, etc..)

Ideally: we would like to know “everything” about all galaxies in a given, large volume ………
Observables in Galaxy Surveys

For large numbers of galaxies we expect to observe:

- Apparent flux in different wavelengths
- Spectroscopic data (redshifts, diagnostic line indices, internal velocity dispersions)
- Morphologies/structural parameters
- Apparent sizes (radii, scale parameters)
- Association with large scale structures (clusters or small groups)
Complications:

- For point-like sources, we are flux limited, with the flux limit depending on the waveband used.
- For extended sources, we are surface brightness limited, as determined from the contrast of the object with respect to the background.
- Completeness of a survey to a given flux limit.
- For any given galaxy, the observed flux in any band, corresponds to a different rest-frame band, depending on the redshift of that galaxy.
- Selection wavelength often indicates the type of galaxies dominating a given survey.
- Be aware of sources of BIAS…
Some Consequences

- Impracticability of nearby, volume limited samples:
  - Given a flux limit $f_{\text{lim}, \lambda}$ any object of luminosity $L_\lambda$, can be seen only within an volume $V = d\Omega \ast (L/(4\pi f_{\text{lim}, \lambda}))^{3/2}$
  - In practice, it means one only needs to know the maximum volume within which the object would have in the survey

From the 2DFRS
K-Corrections

\[ K(z) = -2.5 \log \left[ (1+z) \frac{L_{(1+z)\nu}}{L_\nu} \right] \]
Galaxy Surveys: the present-day luminosity function

- Luminosity function:
  - basic, long-standing statistic to describe the galaxy population: described the space density of galaxies at a given luminosity (or absolute magnitude):

- Often parameterized as a “Schechter function” (1976), to be a power-law at the faint end and an exponential at the brightest end, with a characteristic luminosity $L_\star$

\[
\phi\left(\frac{L}{L_\star}\right)d\left(\frac{L}{L_\star}\right) = \phi^\star\left(\frac{L}{L_\star}\right)^\alpha e^{-\left(\frac{L}{L_\star}\right)}d\left(\frac{L}{L_\star}\right)
\]
To address these questions, we need multi-waveband galaxy surveys

Great Observatories Origins Deep Survey (GOODS)

Cosmic Evolution Survey (COSMOS)

Hubble Ultra-Deep Field (HUDF)

Coma Hubble Treasury Program
The multi-λ Milky Way

radio (408MHz)
H\textsc{i}
radio (2.5GHz)
H\textsubscript{2}
infrared
mid-infrared
near-infrared
optical
x-ray
gamma ray
Multiwavelength galaxy

From the ultraviolet through to the near-infrared, different stellar populations are visible, and dust has more, or less impact.

The characteristics at each wavelength for all galaxies give a cumulative measurement.
Atmospheric transmission I

The atmosphere is only really transparent in the optical, near-IR, and radio windows.

Sub-millimeter!
Atmospheric transmission II

Need to combine ground & space projects to probe all wavelengths.
What data do we need?

• A large-area, deep survey
  – Need **much** more area than the Hubble Deep Fields
  – Need comparable **depth**

• High-resolution and multi-wavelength data
  – Need to follow morphology through cosmic time

• Large wavelength coverage (colors)
  – provide redshift constraints for very faint sources
  – Chandra, ACS, Spitzer, Radio + sub-mm probe the overall energetic output, dust obscuration
Great Observatories Origins Deep Survey (GOODS)

Medium Deep Surveys of Large Areas – designed to study formation and evolution of galaxies and to search for high redshift galaxies
The GOODS Treasury/Legacy Mission

**Aim:** to establish deep *reference* fields with public data sets from X-ray through radio wavelengths for the study of galaxy and AGN evolution of the broadest accessible range of redshift and cosmic time.

GOODS unites the deepest survey data from NASA’s Great Observatories (HST, Chandra, SIRTF), ESA’s XMM-Newton, and the great ground-based observatories.

**Primary science goals:**

- The star formation and mass assembly history of galaxies
- The growth distribution of dark matter structures
- Supernovae at high redshifts and the cosmic expansion
- Census of energetic output from star formation and supermassive black holes
- Measurements or limits on the discrete source component of the EBL

**Raw data public upon acquisition; reduced data released as soon as possible**
A Synopsis of GOODS

GOODS Space

- **HST Treasury**
  - B, V, i, z
  - $\Delta \theta = 0.05$ arcsec, or $\sim 0.3$ kpc at $0.5<z<5$
  - 45 days cadence for Type Ie Sne at $z\sim 1$

- **SIRTF Legacy**
  - 3.6, 4.5, 5.8, 8, 24 $\mu$m

- **Chandra** (archival):
  - 0.5 to 8 KeV
  - $\Delta \theta < 1$ arcsec on axis

- **XMM-Newton** (archival)

GOODS Ground

- **Subaru** Large-area BVRiz imaging and narrow-band surveys
- **ESO VLT** Full spectroscopic coverage in CDF-S
  - Ancillary optical and near-IR imaging
- **Keck**, access through GOODS’ CoIs
  - Deep spectroscopic coverage
- **NOAO** support to Legacy & Treasury
  - Very deep U-band imaging
- **Gemini**
  - Optical spectroscopy, HDF-N
  - Near-IR spectroscopy, HDF-S
- **VLA**, ultra deep HDF-N (+**Merlin, WSRT**)
- **JCMT + SCUBA** sub-mm maps of HDF-N
The Great Observatories origins Deep Survey (GOODS)

Aim: Unite extremely deep, multiwavelength observations to create a public, legacy data set for exploring the distant Universe.

Deepest X-ray observations

HST/ACS Treasury program

Spitzer Legacy program

ESO/NOAO/… follow-up programs (imaging, spectroscopy)
We almost give you the Moon
ACS

B = 27.2
V = 27.5
i = 26.8

\[ \Delta m \sim 0.7-0.8 \]

WFPC2

B = 27.9
V = 28.2
I = 27.6

AB mag; S/N=10
Diffuse source, 0.5" diameter
Add ~ 0.9 mag for stellar
sources
5-Epoch stack
5-Epoch stack – bright stretch
Cosmic Evolution Survey (COSMOS)

LARGEST amount of Hubble Space Telescope time ever awarded to a single project (20% of the Hubble time in one cycle)

Medium deep survey of a VERY LARGE area (2 sq. deg) to study properties of galaxies as a function of environment, SFR, morphology, redshift, luminosity
Cosmic Evolution Survey (COSMOS)

• large area -- 1.4 x 1.4 deg
  => cover largest large scale structures

• high sensitivity ( I > 28.6 mag AB , 5σ)
  => morphology of L* galaxies at z < 2

• sensitivity + area
  => 2x10^6 galaxies , unusual objects at higher z

• equatorial  => multi-λ observations from all tel.
17 orbits
10/31/03

1.4 deg
1.4 deg
130 orbits
3/31/04
1.4 deg

ACS I-band

270 orbits as of 6/15

Cycle 12
270 orbits
5/14/04
Cycle 12 & 13
590 orbits

NICMOS-3
1.6 \mu m -- 24mag
\sim 7\% of area
B. Mobasher

Cosmos

1.4 deg.

2 million gal.

like SDSS at
z = 0.5 -- 5
COSMOS

Telescopes:

- Hubble -- very fine & sensitive optical images
- XMM -- xray imaging
- Galex -- ultraviolet imaging
- Spitzer -- Mid IR w/ IRAC

- Subaru -- multiple color imaging
- VeryLargeArray -- radio imaging
- ESO-VLT & Magellan-- opt. spec. ~ 45,000 gal.
- NIR -- NOAO, UH88, UKIRT…
GOODS and COSMOS offer:

- Extensive multi-waveband surveys from radio to X-ray
- A number of independent SF diagnostics: X-ray, UV, Hα, IRAC (3.6-8.0 mm), MIPS (24 mm), radio (1.4 GHz)
- Large area coverage (2 sq. deg.) – COSMOS
- Deep ACS data and rest-frame morph - GOODS
- HST/ACS morphologies (B/D, Sersic, concentration, asymmetry, clumpiness)
- Accurate photometric/spectroscopic redshifts and spectral types (from early-type to starburst)
- Galaxy stellar masses
Hubble Ultra-Deep Field

Why Ultra-deep?

Or when counting is not enough

• In any survey of high redshift galaxies one obtains more objects by widening the area rather than increasing the depth

• However, extra depth is *necessary to discover a new class of objects* or determine the properties of a class of objects at the limit of our detection
The Renaissance after the Dark Ages

Hubble Ultra Deep Field

Here Now

Hubble Deep Field

end of reionization

primordial galaxy

S1

H II

$T_{IGM} \sim 10^4 \, \text{K}$

$T_{IGM} \sim 4z \, \text{K}$

$z \sim 10^3$

$z \sim 8$

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Hubble Ultra-Deep Field (HUDF)

The DEEPEST image of the Universe ever obtained

Search for the highest redshift galaxies.

Study of the re-ionization of the Universe

Extending study of star formation rate to the highest redshifts
Star formation and metal production history of the Universe

Based on Madau et al. 1996
Star formation and metal production history of the Universe

Based on Madau et al. 1996
HUDF Summary

400 orbits, over 4 months:
Sept-Oct (40 d), Dec-Jan (40 d)

Total exposures ($10^6$ seconds)

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<th></th>
<th>B</th>
<th>V</th>
<th>I</th>
<th>z</th>
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$10\sigma$ sensitivity (point source):

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$10\sigma$ sensitivity (extended source 0.5"):

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<td>28.7</td>
<td>29.0</td>
<td>29.0</td>
<td>28.4</td>
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</table>

Faintest object: $31.1^m$ ($5\sigma$)

NICMOS parallel fields: deepest near-infrared images ever taken
HUDF vs GOODS

GOODS CDFS – 13 orbits

HUDF – 400 orbits
Lecture # 2

Photometric Redshift Measurement

Search for High redshift and new population of galaxies

Reionization of the Universe

Evolution of the star formation rate and mass function
Crisis in the Cosmos?

Old Galaxies in a Young Universe?

We have discovered a new population of very massive and evolved galaxies at high redshifts

Mobasher et al 2005

Wiklind, Mobasher et al 2006
Use near- and mid-IR to select high redshift and evolved galaxies

The Balmer break is a prominent feature for stellar populations age \( t > 100 \) Myrs
Dusty starburst at $z \sim 2.5$

Post starburst at $z \sim 7$

old Elliptical at $z \sim 2.5$

dust-free post-starburst $z \sim 7$

dusty starburst $z \sim 2.5$
K-selected sample from GOODS-S

HST/ACS (BViz);
VLT/ISAAC (JHKs);
SST/IRAC (3.6, 4.5, 5.8, 8μm)

5754 sources
155 / 85 selected; 14/12 z > 5 (total 17)
~82% complete at K_{AB} = 23.5

Model tracks from BC03

Post-starburst galaxies (age 0.2–1.0 Gyr)
Elliptical (age > 3 Gyr)
Dusty starburst galaxies
Multi-waveband Galaxy Surveys:
GOODS, COSMOS, HUDF, Coma

HST/ACS

VLT/ISAAC

SST/IRAC

B > 30.61  i > 30.88
V > 31.02  z > 30.26
ACS$+$NICMOS$+$ISAAC
JD2 (J-dropout) in HUDF
(Mobasher et al. 2005)

$z = 6.5$
no current star formation
age $\sim 0.65 - 1.0$ Gyr
$E_{B-V} = 0.0$
$M_* = 5 \times 10^{11} \, M_\odot$
$Z \sim 0.2 - 1.0 \, Z_\odot$
What is the space density of high redshift massive galaxies?

We selected the Balmer Break Galaxies in the GOODS area.
There is no ‘clean’ way of color selecting old z > 5 galaxies

Use a two-step process:

Color selection:
• The main index is the $K_s$–3.6$\mu$m color
• Use J–K and H–3.6$\mu$m as secondary color
• This will result in a relatively large fraction of interlopers

Population synthesis models (Bruzual & Charlot 2003):
• Redshift range  $z = 0.2 - 8.6$
• Age range = 5 Myr - 2.4 Gyr
• Calzetti attenuation law $E_{B-V} = 0.0 - 1.0$
• IGM absorption
• Metallicities $Z = 0.2, 0.4, 1.0, 2.5 Z_\odot$
• Salpeter IMF: 0.1 – 100 $M_\odot$
• Star formation history: exponentially declining SFR
  $\tau = 0 - 1.0$ Gyr
$z = 5.1$
$E_{B-V} = 0.0$
$\text{age} = 0.9 \text{ Gyr}$
$\tau = 0.1 \text{ Gyr}$
$M_* = 4 \times 10^{11} \text{ } M_\odot$

$z = 5.0$
$E_{B-V} = 0.0$
$\text{age} = 0.8 \text{ Gyr}$
$\tau = 0.2 \text{ Gyr}$
$M_* = 5 \times 10^{10} \text{ } M_\odot$
$z = 5.6$
$E_{B-V} = 0.025$
$\text{age} = 0.8 \text{ Gyr}$
$\tau = 0.2 \text{ Gyr}$
$M_* = 1 \times 10^{11} \text{ M}_\odot$

$z = 4.9$
$E_{B-V} = 0.150$
$\text{age} = 1.0 \text{ Gyr}$
$\tau = 0.3 \text{ Gyr}$
$M_* = 2 \times 10^{11} \text{ M}_\odot$
Gemini GNIRS spectroscopy of the $z \sim 7$ candidate:

No lines detected

Ly$\alpha$ (\(\lambda 1216\)) $z \sim 7$ (0.97 micron)

H$\alpha$ (\(\lambda 6563\))
- $z \sim 0.8 - 1.2$ J-band
- $z \sim 1.3 - 1.8$ H-band
- $z \sim 2.0 - 2.8$ K-band
In addition:

- Gemini-S GNIRS cross-dispersed
- VLT FORS
- HST ACS Grism
- Keck NIRSPEC

Keck and VLT: sensitive to Ly\(\alpha\) emission from galaxies at 6.8 < z < 8.0 with SFR 3-5 M\(_{\odot}\)/yr

Keck and Gemini: sensitive to H\(\alpha\) emission from galaxies at 0.8 < z < 2.8 (with gaps) with line fluxes 10\(^{-17}\) - 2 \(\times\) 10\(^{-18}\) erg cm\(^{-2}\) s\(^{-1}\)

Ly\(\alpha\) (\(\lambda\)1216) z ~ 7 (0.97 micron)

z ~ 0.8 - 1.2 J-band
z ~ 1.3 - 1.8 H-band
z ~ 2.0 - 2.8 K-band
Conclusions

• Color selection (NIR & IRAC) + photometric redshift can identify z>5 galaxies with ages >100 Myr, with masses in excess of $10^{11} \, M_\odot$. The selection is mainly based on identifying the Balmer break over K-3.6μm.

• In the GOODS South field we find 11 such candidates (including JD2).

• The objects found are characterized by little or no ongoing star formation, ages of several 100 Myrs, masses of $\sim 10^{11} \, M_\odot$ and very little dust extinction.

• The number density of the Balmer break galaxies is $4-5 \times 10^{-5} \, \text{Mpc}^{-3}$ which is higher than for corresponding dark matter halos assuming $M_{\text{baryon}}/M_{\text{total}} \sim 0.06$.

• If the stellar masses are overestimated by a factor 3-4, the number density agrees with that of dark matter halos (top-heavy IMF, synthesis models, …).

• Formation redshifts range 6 – 25+, within the reionization era.
Search for High Redshift Galaxies

What are the properties of the highest redshift galaxies?

What is the SFR, mass, morphology of high-z galaxies?

How we find the highest redshift galaxies?

Mobasher et al 2006
Ajiki, Mobasher et al 2005
Wiklind, Mobasher et al 2007
By looking at distant regions in the Universe, we look back in time. By looking for the most distant galaxies, we look at the beginning of the Universe.
Search for the Highest Redshift Galaxies

- Drop-out technique in which a galaxy is not detected at shorter wavelengths (due to extinction of short wavelength light by IGM) while, detected at longer wavelengths
- Narrow-band search, targeting for rest-frame Lyman α emission lines, shifted to high redshifts
Finding High-Redshift Galaxies

• Theory predicts that dark matter structures form at \( z \sim 20-30 \)

• It does not clearly predict galaxies, because we do not fully understand star formation

• We need to push empirical studies of galaxy evolution to the highest redshifts

• We collected the deepest and largest quality samples of galaxies at \( z \sim 4 \) through \( z \sim 6 \)
LBGs are star forming galaxies at $z > 2$, identified by the color signature of the Lyman limit and Ly-α breaks.

First studied in large numbers by Steidel et al. (1995-2001).
Now $\sim 1000$ with measured redshifts.
Galaxies at $z \sim 6$
Very Red Objects

Candidates for galaxies at redshifts greater than 6
Near-Infrared Search for $z \sim 7$ Galaxies

To survey the GOODS-N field with a new filter with peak sensitivity at 1 $\mu$m to search for redshift $\sim 7$ galaxies (z-band dropouts)

Five nights of Subaru (S-Cam) was awarded in March 2006. This technique is 100 times more efficient than performing a near-IR survey.

B. Mobasher and M. Ouchi
Detect $z \sim 7$ gal. to $z_R \sim 26.3$
Expect $\sim 60$ gal. at $z \sim 7$ over 900 arcmin$^2$

5 Nights of Subaru time is awarded
(Mar. 06)
Multi-waveband Galaxy Surveys: GOODS, COSMOS, HUDF, Coma
Narrow-band surveys (NB816) of GOODS and COSMOS are completed with Subaru. These surveys target star-forming galaxies at certain redshifts. The NB survey provides

\[ \text{H}\alpha \text{ emitting galaxies at } z=0.24 \]
\[ \text{Lyman } \alpha \text{ emitters at } z=5.7 \]
SFR, stellar mass, morphology and rest-frame properties of star-forming galaxies at $z = 5.7$

Mobasher, B. et al 2006
We have found over 110 Lyman α Emitters in the COSMOS field using narrow-band imaging

More than any other single survey
Examples of LAEs
@ z=5.7

<table>
<thead>
<tr>
<th>COSMOS</th>
<th>B</th>
<th>V</th>
<th>r'</th>
<th>i'</th>
<th>NB816</th>
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8″
LAE $z_{\text{spec}} = 5.7$

$E_{B-V} = 0.05$

Single SF burst

$\tau = 0.0 \, \text{Gyr}$

$= 8 \times 10^9 \, M_{\text{sun}}$

Mobasher et al. 2006
LAE $z_{spec} = 5.7$
$E_{B-V} = 0.05$
Single SF burst
$\tau = 0.0$ Gyr
$M = 8 \times 10^9 \, M_{\odot}$

$LBG \, z_{spec} = 5.8$
$E_{B-V} = 0.0$
Continuous SFR
$\tau = 0.6$ Gyr
$M = 3 \times 10^{10} \, M_{\odot}$
Serendipitous single emission lines: Lyman-α?

Main possibilities:

i. Unresolved [OIII];
ii. Hα;
iii. Ly-α;

Reinforcing features:

i. Symmetric line
ii. Associated lines or D4000 break
iii. Asymmetric line & cont’m break
Confirming high-redshift galaxy candidates is a tough game!

Weak features (lines or breaks), very high-background sky and OH telluric emission lines, as well as dropping CCD sensitivities...
Conclusions

• We performed morphological studies of LAEs at $z = 5.7$.
• We discovered 110 LAEs in COSMOS field
• We find an average mass of $8 \times 10^9 \, M_{\text{sun}}$ for LAEs
When did Super-Massive Black Holes Form?

Chandra and Hubble working together:

we found 7 sources detected by Chandra but not detected by HST. Among them, most likely there are:

- The most distant active galaxies (super-massive black holes) ever observed, at z>7?

- SIRTF will determine whether this interpretation is correct or not
The Most Distant Black Holes (z>7)?

HUDF fully in 1st-epoch overlap region!
The history of the cosmic star formation activity:

We found that at $z \sim 6$ the cosmic star formation activity was nearly as vigorous as it was at its peak, between $z \sim 2$ and $z \sim 3$.

- Dust obscuration not truly constrained
  - Escaping UV radiation only a small fraction
  - Large progress with SIRTF
- Selection effects
  - Estimated from detailed numerical simulations
- No correction for $(1+z)^4$ dimming
  - How much light are we missing?
  - To explore further with full-depth ACS data

Giavalisco et al. 2003
Identifying high-z Galaxies

• From modeling & observations, the Steidel-type optical color-selection for LBGs is fine (e.g. Idzi et al 2003); but perhaps just not deep enough...
• Other techniques for finding $z>\sim2$ galaxies (e.g. by identifying $\sim4000\text{A}$ breaks via J-K selection) do reveal possibly significant galaxy populations.
• Narrow-band surveys
The GOODS “space” fields

The GOODS space fields: HDF-North & CDF-South

Extremely deep CXO X-ray observations: 2Ms & 1Ms

- ~33x solid angle of combined HDFN+S central fields
- ~4x solid angle of combined HDFN+S flanking fields
- ~2.5x solid angle of WFPC2 Groth Strip
- ~22 x 35 $h_5^{-1}$ Mpc comoving transverse extent at $z = 3$

Deepest SIRTF coverage from 3.6 - 24 $\mu$m (160 $\mu$m from GTO surveys)

“Near-HDF” depth 4-band HST/ACS imaging

Two fields provide:
- Access to observers in both hemispheres
- Control of cosmic variance

Both fields at high galactic & ecliptic latitude, with low zodiacal & galactic foregrounds, $\Lambda$(HI), stellar & radio contamination, etc.
SIRTF vs CXO layout
Primitive K-selected surveys as tests for GF models

The K&C c. 1998 ingredients:
SCDM +
late star formation +
non-K based LFs

There is a marked difference between "Passive luminosity evolution" and LCDM-based Semi-Analytic Models, by $z \sim 1$

Kauffmann & Charlot 1998
An old galaxy at $z=1.55$

LBDS 53W091
Lyman-break dropouts
($z>2$)
\[ N(>z) \text{ of } K_{AB} < 22 \]
galaxies

Note discrepancy at \( z \sim 2 \) and beyond...
semianalytic models underpredict -both- 'red' and 'blue' populations

Somerville et al. 2003
At redshifts z~2, current semianalytic models are missing both the blue & red galaxy populations seen in the GOODS data; including the EROs.

Somerville et al. 2003
models vs observations

- Well-constrained LCDM-based models (Somerville et al), that match many observations at $z \sim 0$ AND $z \sim 3$ underpredict many massive &/or star-forming galaxies at $z \sim 2-3$.
- Is this a fundamental problem? Construct the other moments & see...
Measuring SFRs

• nebular emission lines (spec)
• rest-UV continuum (imaging or spec.)
• non-AGN X-ray emission (CXO)
• radio luminosity (VLA, ATCA)
• sub-mm emission (SCUBA, APEX...)
• GOODS' 24μm (PAHs at z~2), GTOs' 70-160μm
To measure SFRs (etc)...

• Need to find the galaxies,
• be confident about their redshifts (or redshift distributions)
• make good measurements
• try to determine the completeness!
  – => what populations may be missed by magnitude limits, obscuration, etc? :/
Galaxies to $z \sim 2$

- Photometric redshifts are calibrated and work well to $z \sim 1.5$
- At redshifts above $z \sim 0.8$, it is important to use near-IR selection (K)
- Certain color-selection limits restrict redshift ranges (e.g. R-Ks or J-Ks), followed up by spec-zs or photo-zs
The Assembly of Galaxies

- The ultimate goal is to measure the distribution function of stellar mass and star formation rates over time:

\[ f(M, \frac{\partial M}{\partial t}, t) \]

This encapsulates the assembly history via all modes -- quiescent star formation, starbursts, &c.
Moments...

- The moments of this distribution, are:
  - the comoving star formation rate, SFR(t):
    \[
    SFR(t) = \int \int \frac{\partial M}{\partial t} f(M, \frac{\partial M}{\partial t}, t) \, dM \, d(\frac{\partial M}{\partial t})
    \]
  - the mass function, f(M,t):
    \[
    f(M,t) = \int f(M, \frac{\partial M}{\partial t}, t) \, d(\frac{\partial M}{\partial t})
    \]
- More primitive approaches (e.g. redshift distributions) are easier & work. How do these fare?
**SPITZER Imaging**

 GOODS sensitivity

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<td>24</td>
</tr>
<tr>
<td>Field of View</td>
<td>5'x5'</td>
<td>5'x5'</td>
<td>5'x5'</td>
<td>5'x5'</td>
<td>1'x1.2'</td>
<td>5'x5'</td>
</tr>
<tr>
<td>Number of Pixels</td>
<td>256x256</td>
<td>256x256</td>
<td>256x256</td>
<td>256x256</td>
<td>33x45</td>
<td>128x128</td>
</tr>
<tr>
<td></td>
<td>20-80μJy</td>
<td>32x32</td>
<td>2x20</td>
<td>0.5'x5'</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
SPITZER-GOODS objectives

• Tracing the stellar mass assembly history of galaxies out to $z \sim 5$ or beyond
  – Rest-frame K-band light at $z \sim 3$
  – Rest-frame $\lambda > 1 \, \mu m$ to $z = 7$
  – $24 \, \mu m$ to trace obscured star formation in “ordinary” LBGs and LIRGS at $z \sim 2.5$
  – Wide variety of other SFR indicators (radio, UV, emission line, far-IR/sub-mm)

• Census of energetic output from obscured AGN and star formation at high redshift

• Measuring the discrete source component of the EBL at 3.6-24 $\mu m$
Measuring stellar masses

• Method(s):
  – Minimize $\chi^2$ fit with SEDs, get M/L
    • Adopt long-$\lambda$ luminosity & mass conv.
    • Use Bell & de Jong or Bell et al relations between rest-frame colors and M/L ratio

• Uncertainties...:
• Initial mass function choice (usually Kenn or Salp)
• Universality of IMF
• Star formation history
• Dust effects (and reddening law)
• Luminosity/mass function behavior (at faint end)
Bell et al stellar masses

• The relation between rest-frame optical colors and the M/L ratio (from SED-fitting) is surprisingly tight!
  • => well-constrained SED & z
    – -> rest-frame colors (e.g. B-V)
    – -> M/L ratio x luminosity (e.g. at V)
      • stellar mass @V
Uncertainties in $M/L$ determination are ~30%, for fixed IMF choice.

Can convert $M/L$ values between IMFs by an additive constant in dex (Bell et al. 2003).
SIRTF-GOODS

- Data still pending --
- Test-fields & First Look Survey data being acquired now
- First SIRTF data released to the public in two weeks
- First GOODS observations start in early '04.
Finding Galaxies at Less Than 10% of the Cosmic Age

B-dropouts, $z \sim 4$, 11% C.A.

V-dropouts, $z \sim 5$, 8.5% C.A.