Galaxy Evolution

1. Common Goals

There were many similarities among the galaxy evolution science cases. Broadly speaking, the common major goals seemed to be:

1. **Galaxy number counts as a function or redshift to z = 5 or 6, and to luminosities well below $L^\star$.** Most science cases advocate a large optical survey that can be examined as a function of redshift, environment, morphology, luminosity, abundance, star formation rate, etc. This survey would yield rough information on abundances and stellar populations with "integrated" spectra (i.e., no spatial information). This can be the same redshift survey used to study large-scale structure.

   Requirements: A wide-field optical spectrograph that operates in natural seeing, with capabilities at $R = 500 - 1000$ for the galaxy survey; the field should be wide enough to observe $0.5 - 1 \times 10^6$ galaxies to magnitudes of $R \sim 26.5$ on the timescale of a year.

   Issues: How many galaxies are enough? (The NOAO, CELT, and Canadian cases discuss this at length and settle on a survey roughly the size of the SDSS.) How accurate are the abundances and how ambiguous is the stellar population information?

2. **Mass measurements, to determine galaxy properties as a function of mass.** Luminosities may not be good indicators of total mass as M/L varies substantially during and soon after epochs of star formation. Mass measurements are possible with multiple techniques:

   - **Strong gravitational lensing** (not discussed extensively).
   - **Dynamical masses of galaxies** at all redshifts to $z = 5$, from emission-line and absorption-line kinematics. These measurements will also help distinguish between star-forming lumps within single galaxy and merging sub-units.

     Requirements: A NIR spectrograph with AO correction and multiple IFUs.

     Issues: The spatial resolution of a diffraction-limited 30m GSMT is certainly sufficient; even the most compact galaxies would have many resolution elements across their diameters. The main issue is sensitivity. At $z > 1.5$, absorption line spectra will certainly only encompass the central high surface brightness regions of early-type galaxies; these studies will likely not require sampling at the diffraction limit. The sensitivity to line emission depends entirely on how clumpy the emission is. Unresolved lumps with star formation rates above one solar mass per year are visible at high redshifts (see figure), but if the emission is uniform even the Lyman break galaxies will be difficult to observe. How many independent spatial points do we need to distinguish assembly and/or outflows from circular motion?

3. **Spatially-resolved abundances and ages of stellar populations.** Measurements of the internal abundances and age structure of galaxies will help track the assembly of galaxies and the enrichment of the IGM through outflows. Observations in the rest-frame optical will be directly comparable to the low-z observations our current knowledge is based on. (Spatially unresolved NIR measurements would obviously be useful here, too.)

   Requirements: Similar to the case of dynamical masses, the requirements are AO-corrected IFU's in the NIR, with the best possible multi-plexing to increase the sample size.

Issues: In addition to all the concerns regarding the dynamical masses case, how well do existing theories predict the internal abundance and stellar population structures of galaxies? When will galaxy formation predictions "catch up" to the required sub-kpc resolution? Also, what ranges of redshifts allow measurements of enough emission-line strengths between absorption and OH features?

4. **Observations of the first star-forming galaxies, the objects responsible for re-ionization of the Universe ($z > 6$).** Most science cases advocate observing the Lyα emission from these galaxies, which falls in the NIR up to $z \sim 19$.

   Requirements: Narrow-band imaging or IFU's in the NIR, with good AO correction.

   Issues: Sensitivity is a big issue. Little is known about the predicted line strengths and, more importantly, the compactness of the star formation. Also, what will the GSMT add to the knowledge gained by NGST? (The R=4 filter set proposed for NIRCam on NGST claims roughly a 3% photometric redshift accuracy at high redshift.)

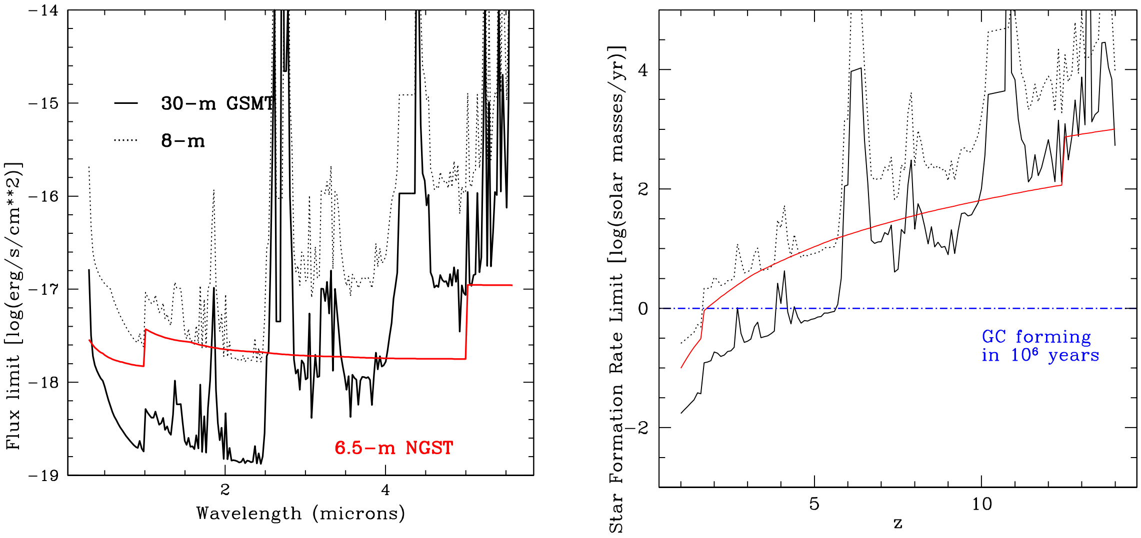

Fig. 1.— Sensitivity to emission-line flux (R= 3000) as a function of wavelength or redshift for a 10,000-second exposure with an 8-meter ground-based telescope (*dotted line*), a 6.5-meter NGST (*solid red line*), and a 30-meter GSMT (*solid black line*). For the ground-based telescopes, we assume optimistic high-level AO correction. We assume that the source is unresolved both spatially and spectroscopically and plot limits for a line detection with S/N= 10. *Left panel:* the emission-line flux limits as a function of λ. *Right panel:* the limiting star formation rate as a function of redshift in the [OII]λ3727 line using the Kennicutt (1998) conversion between SFR and line flux ($q_0 = 0.1$, $H_0 = 70$ km/s/Mpc). The dot-dashed line at $\log[SFR] = 0$ shows the flux expected from a globular cluster forming in 10^6 years. If many such clusters form at the same time, these compact star-forming regions could serve as tracers of dynamical masses and/or the kinematics of gravitational collapse to $z \sim 6$.

2. Possible omissions

These cases were not particularly emphasized:

1. **Photometric redshift surveys.** Photometric redshifts are good enough for many purposes. How many of the redshift survey goals can be achieved with photometric redshifts alone?
2. **Wavelengths $> 2.2\mu$m.** Most science cases point to NGST for these wavelengths, but with good background subtraction, at high resolution, NGST performance may be comparable to the GSMT in some regions between 3-4 μm (see figure). The ground provides much more versatility, and the gains in spatial resolution of the GSMT are substantial.
3. **Galaxy morphology at the diffraction limit in the NIR.** The resolution of NGST is 550-700 pc in K, whereas the diffraction limit of the GSMT is 120-150 pc in K at z=2-5 ($\Omega_\Lambda = 0.7, \Omega_{\rm matter} = 0.3, {\rm h} = 0.7$). Sub-kpc scales are of great interest for many morphological issues. For example, identifying late-stage mergers (e.g., double nuclei in ULIRGs), because counting mergers in the later stages would be the most direct means of measuring the merger rate. (Compared to well-separated pair of galaxies that may be interlopers, late-stage mergers are relatively unambiguous.) Sub-kpc scales are also of great interest for secular evolution and other processes of gas infall that may lead to bulge enhancement or late-type bulge formation in spiral galaxies.
4. **Synergies with other planned facilities** like ALMA and the SKA.

3. Summary of possible follow-up studies

1. The requirements for halo mass measurements through strong gravitational lensing.
2. A detailed analysis of the expected clumpiness of high-z starbursts. (E.g., to what redshift can we measure the kinematics of the forming superclusters in the Antennae? etc.).
3. What differences in spatial abundance and star formation properties do different theories for hierarchical assembly predict? What capabilities do we need to distinguish between them with a GSMT?
4. When combined with photometric redshifts or spectroscopic redshift surveys, how well can high-resolution morphology studies at $z = 2 - 5$ determine the merger rate as a function of redshift?
5. Design of a large photometric redshift survey.