Benjamin Weiner Steward Observatory November 10, 2013 **Research Interests**

My research studies galaxy evolution with emphasis on star formation histories, gas accretion and outflow, and galaxy kinematics. I am working on projects that link low and high redshift galaxies, on spatially resolved measurements of distant galaxies, and on links between phases of galaxy evolution: mergers, IR-luminous galaxies, and QSOs. These projects use multi-wavelength data including HST, Spitzer and Herschel mid- and far-infrared, and ALMA radio observations, combined with large redshift surveys, including SDSS at $z \sim 0.1$ and DEEP2+CANDELS at $z \sim 1-2$. Much of this work attempts to understand the $z \sim 1-2$ universe, where the star formation rate was $\sim 10\times$ higher than now, and link it to the galaxies we see today.

My recent publications study the star formation and dynamical histories of $z \sim 1$ galaxies, and their gas content, accretion, and outflows. Some of my chief results are: mapping the resolved kinematics and disk and halo masses of local barred galaxies (Weiner et al 2001); measuring spatially resolved kinematics for $z \sim 1$ galaxies, showing the existence of rotation and dispersion-dominated galaxies (Weiner et al 2006); measuring the evolution in the Tully-Fisher relation to $z = 1$ and links between kinematic and morphological disturbances (Weiner et al 2006; Kassin et al 2007); showing the existence of a SFR-stellar mass "main sequence" for galaxies to $z > 1$ (Noeske et al 2007); and showing that star-forming galaxies at $z > 1$ are all driving highly mass-loaded outflows, probably enriching the circumgalactic medium (Weiner et al 2009).

My current and future research is on HST slitless spectroscopic surveys of galaxies at $z \sim 1-2$; using galaxy clustering in large surveys to understand the nature of IR-luminous galaxies and AGN; Herschel and ALMA observations of star forming galaxies near and far to understand the distribution of gas, dust and star formation in them; and spectroscopy of galactic outflows and galaxy-Mg II absorption system associations found in the BOSS survey, to constrain the gas content of galaxy halos. In the longer term I aim to lay the groundwork for spatially resolved spectroscopy with JWST and its near-IR and mid-IR probes of spectral features critical to understand physical conditions in star-forming galaxies, and studies of the ISM at millimeter and radio wavelengths with ALMA, JVLA, LMT and eventually CCAT, that complement far-IR data from Spitzer and Herschel.

I have worked on instrument design, commissioning, and data analysis for imaging, spectroscopy, and 3-D (integral field) datacubes; the design, planning, and execution of large survey projects; and designing software pipelines, data structures and models, and statistical analysis. I have built reduction software and analyzed 3-D cubes from optical Fabry-Perot data and from radio 21 cm observations with the VLA, and from fluid dynamical models (Weiner et al 2001). I also played a major role in the construction and use of the Maryland-Magellan Tunable Filter imager (Veilleux et al 2010). I was closely involved with the DEEP1 and DEEP2 surveys, designed software for 2-D analysis of kinematics and rotation curve data for high-z galaxies (Weiner et al 2006; Kassin et al 2007); and for spectral fitting and analysis of complex restframe-UV galactic wind absorption lines (Weiner et al 2009). I developed redshift measuring and line fitting software, which we used to measure star formation and the star formation-mass sequence (Noeske et al 2007). I have also worked on Spitzer/IRS mid-IR spectroscopy and built data reduction procedures for extracting spectra from very faint objects (Rujopakarn et al 2012).

Currently I am working on projects with the AGHAST HST/WFC3 survey of the GOODS-N field with near-IR slitless spectroscopy, of which I am PI (HST PID 11600); on Herschel spectroscopy of far-IR lines from star forming regions in IR-luminous disk galaxies; and with my involvement in an IRAM Large Program to measure gas mass through mm-wave CO detections in $z > 1$ galaxies (Tacconi et al. 2010). These involve spatially resolved spectroscopy with HST/WFC3; mid- and far-IR spectroscopy prefiguring JWST/MIRI science; and synergy between HST-resolved imaging and ALMA spatially resolved maps.

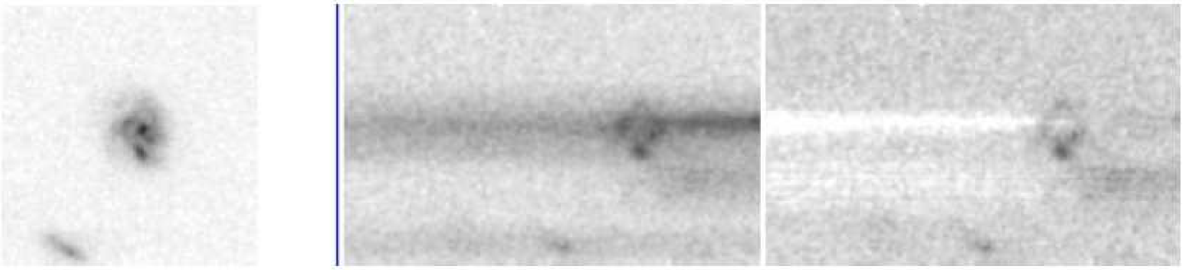

Figure 1: WFC3-IR imaging and slitless spectroscopy of a z=1.25, highly star forming IR-luminous disk galaxy, SFR $\sim 100\ M_\odot$/yr, from our AGHAST survey. Left: F140W direct imaging; the image is $6''$ across. Middle: G141 grism spectrum. Right: continuum subtracted spectrum, yielding an effective narrow band image of the Hα+[N II] emission. (The light horizontal band is due to contamination by another object spectrum). The clumps in the disk emit strongly in Hα, so we can measure size and individual luminosities; the galaxy center is red and does not emit in Hα, so it is either dust-obscured, or more likely populated by old stars.

Redshift surveys in the near-IR with HST/WFC3: The speed and multiplex advantage of WFC3-IR slitless spectroscopy make it possible to carry out surveys of deep extragalactic fields of size 10-20$'$. The AGHAST survey that I am PI of covers most of the GOODS-N field with WFC3-IR grism spectra, spanning 1.1-1.65 μm at low resolution, and the 3D-HST treasury survey (PI Pieter van Dokkum) covers the other 4 CANDELS fields. These slitless grism spectra provide redshifts and emission line flux measurements for $\sim 2000-3000$ galaxies at $0.7 < z < 3$ per deep CANDELS field. A large fraction of my time over the past two years has been devoted to these complex datasets, developing reduction pipelines and software for fitting and quality-checking redshifts and emission lines. These are now mature and we are producing catalogs of redshifts and matching to other wavelengths (e.g. Spitzer and Herschel far-IR, and X-ray) and preparing papers.

The HST near-IR spectra can *identify optically faint but far-IR bright sources, and accurate emission line fluxes and ratios, by themselves or combined with ground-based spectra, allow measurements of extinction, star formation rate, and metallicity* (eg. Hα flux, Balmer decrement, and [O III]/Hβ ratio). A unique aspect is that *the spatial resolution of HST allows measuring the size of the line-emitting region,* so we can study whether the star formation is very concentrated, as in low-redshift mergers and ULIRGs, or more spread out, like disks. Figure 1 shows an example of the WFC3-IR grism resolving a z=1 galaxy into several star-forming Hα emission clumps/regions. This is a precursor to the spatially resolved spectroscopy that will be possible with JWST/NIRSPEC and ALMA, to measure properties (SFR, metallicity, etc) of these regions.

For about ~ 20 galaxies, there are CO detections of molecular gas from the PHIBSS survey with the IRAM interferometer (Tacconi *et al.* 2010), on which Michael Cooper and I are co-Is. Cooper is PI of a HST grism program to study these objects, so we will have detections of dust, gas, and Hα emission, and in some cases *spatial resolution in both CO and Hα to study the Kennicutt-Schmidt relation between gas and SFR surface densities.* Cooper and I are also co-Is on a very large IRAM program (led by L. Tacconi, F. Combes et al) now approved to extend these samples of $z = 0.5 - 2$ galaxies. These prefigure what will come from ALMA.

The HST grism spectra also provide *many redshifts to faint IR magnitudes in the redshift range* $1 < z < 2$ - *several thousand new redshifts over the five CANDELS fields*, thanks to the high multiplex of slitless spectra. Samples this large have not been practical from the ground, will take a long time even with multiple-object near-IR spectrographs such as LUCIFER and MOSFIRE, and some IR wavelengths are blocked. Thus HST redshifts will provide an important resource for photometric redshift calibration, constructing samples for moderate-resolution IR spectroscopic followup with ground-based spectrographs and eventually JWST/NIRSPEC, and calibrating the redshift distribution of faint galaxies, a critical input to LSST weak lensing dark energy measurements.

In the future, I anticipate working with this and deeper HST/WFC3 IR grism spectra, preparatory to high-z science with JWST, e.g. measuring the 4000 Å break to model galaxy ages, studying AGN and metallicity, and sizes of star forming regions, through spatially resolved emission, and designing very deep redshift surveys. We also have begun to follow up grism-selected galaxies with higher resolution IR spectra from LUCIFER and MOSFIRE; an example is our study of AGN emission line diagnostics with MOSFIRE (Trump et al 2013).

Far-IR spectroscopy: the star-forming regions in IR galaxies: I lead another project on the spatial extent of star formation that uses Herschel spectroscopy of far-IR fine structure lines including [C II], and ALMA observations of molecular gas, to probe the physical conditions in star-forming regions of IR-luminous galaxies. Far-IR cooling lines probe the diffuse regions of molecular clouds and star forming regions, as PAH features do in the mid-IR. In local galaxies, $L([\text{C II}])/L_{IR}$ declines with IR luminosity and is especially low for ULIRGs, probably due to higher local gas density and ionization, because the ULIRGs are very concentrated. In a few high-z galaxies where it can be measured, [C II] is stronger than in local galaxies (Stacey *et al.* 2010). Evolution in [C II]/IR ratio may be related to evolution in the mid- to far-IR SED shape and to stronger PAHs in high-z galaxies, all possibly caused by evolution in physical properties (density, ionization) in high-z galaxies. But even with Herschel, measuring [C II] in z=1-2 galaxies was out of reach except for a small number of extremely bright or lensed objects.

I have PI'ed proposals in Herschel Cycle 1 and 2 to obtain spectra of the far-IR lines [C II] 158, [O I] 63, [N II] 122 and [O III] 88 μm lines in 16 disky, IR-luminous galaxies, which I identified from SDSS+IRAS. These are IR-luminous, close to ULIRG luminosities ($L_{IR} \sim 10^{11.5-12} L_{\odot}$, or star formation rate 30-100 $M_{\odot}$/yr) but isolated disks rather than mergers. Such disks are unusual locally as most LIRGs and nearly all ULIRGs are morphologically disturbed merger events. *This disky near-ULIRG sample may be analogs of high-z star forming galaxies at z=1-2*, where LIRGs can be undisturbed galaxies on the SFR-mass "main sequence" (Noeske et al 2007).

We have obtained MMT longslit spectra to measure the spatial extent of star formation in their disks, and extinction and metallicity. I now also have an ALMA cycle 1 program approved to map CO in 6 of the galaxies, probing their molecular gas mass and radial distribution.

Our Herschel spectra show that generally these galaxies have strong [C II] and high [C II]/L_{IR} (Figure 2). The two galaxies with lowest [C II]/L_{IR} are also the least extended in Hα in the MMT spectra. *This supports the idea that [C II]/L_{IR} is related to surface density of star formation,* through effects on the density and ionization parameter in star forming regions. By analogy it suggests that *high [C II] at high z is related to star formation spread out in galactic disks rather than concentrated as in local ULIRGs.* These local IR-luminous disks provide a comparison sample for observations of the far-IR cooling lines at high-z, redshifted into the sub-mm, that will come from ALMA and the LMT and CCAT telescopes. With JWST/MIRI, we will be able to measure mid-IR features (PAHs, emission lines, silicate absorption) from high-z galaxies, correlate these probes of physical conditions in star-forming regions with the far-IR lines, and compare to measurements of surface density using spatially resolved emission lines from JWST/NIRSPEC.

Galactic outflows and absorption lines from the circumgalactic medium: Galactic winds and outflows in the high-z universe are a prime suspect for the enrichment of the IGM, and may cause metal-line QSO absorption systems spatially associated with galaxies. The mass-metallicity relation suggests that winds have ejected metals from low-mass galaxies, but does not tell us whether L^* galaxies drove outflows in the past (Tremonti *et al.* 2004).

I have used co-added spectra from DEEP2 at $z \sim 1.4$ to show that *blueshifted Mg II ISM absorption driven by star formation is ubiquitous in these blue-sequence starforming galaxies, progenitors of today's L^* galaxies* (Figure 2, Weiner *et al.* 2009). We find stronger winds in higher-mass,

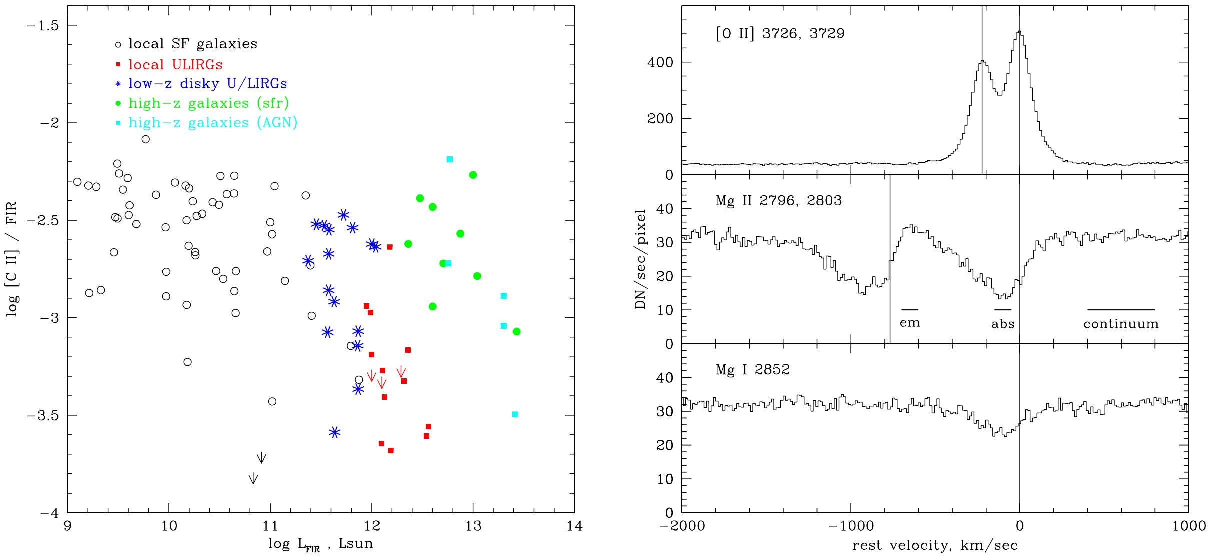

Figure 2: **Left:** Ratio of [C II] 158 μm luminosity to L_{IR}, vs L_{IR}. This ratio declines to high L_{IR}, the "[C II] deficit." The sample of low-z IR-luminous disk galaxies that we measured with Herschel (blue stars) have high [C II], unlike low-z ULIRGs (red squares), but like z=1-3 extreme galaxies (cyan and green points). This supports larger star-forming areas at high z. **Right:** Restframe UV stacked spectra of DEEP2 galaxies at $z = 1.4$. The asymmetric, blue-shifted absorption lines of Mg II and Mg I show strong outflows, which we find are driven by star formation and supernovae (Weiner et al 2009). These constrain models of galactic winds and chemical evolution.

higher-SFR galaxies, which helps to constrain models of wind physics used in cosmological simulations (Finlator & Davé 2008). We have extended this study to lower redshift (Rubin *et al.* 2010); and searched for outflows from post-starburst galaxies and weak AGN with UV spectra from Keck/LRIS-B (Coil *et al.* 2011), to test outflow "AGN quenching" models of star formation. We found only lower-velocity outflows consistent with star formation, suggesting that AGN outflows are not directly responsible for quenching the post-starbursts.

I am now extending this program to study the circumgalactic medium, gas in the halos of galaxies that may be related to both accretion and outflows, with an ancillary target program in the BOSS survey of SDSS-III. In BOSS we take spectra of high-mass galaxies at $z \sim 0.4$ projected close to the line of sight to SDSS-2 quasars.

Our results from the first half of BOSS data show that *strong Mg II absorbers at* $b < 50$ *kpc are detected around* $\sim 50\%$ *of blue and* $\sim 30\%$ *of red massive galaxies.* This implies a cold gas supply within the virial radius of red galaxies, even though their SFRs are low and popular models "quench" the star formation in red galaxies by cutting off the supply of cool gas. We are now planning to extend this survey with higher- resolution followup, and bridge this sample to galaxy-absorber samples from the COS-Halos survey, where the absorbers have HST/COS UV spectra of high ionization lines but the sample of red galaxies is fairly small.

References

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