Session VII

The Next Decade

Stellar Populations - Planning for the Next Decade
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A Golden Decade for Stellar Populations?

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Abstract. People working on stellar populations can look forward to an exciting decade ahead. Investigations of stellar populations lie at the heart of the science cases being used to justify the development of upcoming telescopes and emerging instrumentation technologies. Examples abound, but I will focus on three case studies: (1) Wide field astronomy with upcoming ground-based and space-based survey facilities; (2) Adaptive optics, which has the potential to revolutionize our understanding of stellar populations in both nearby and distant galaxies; (3) The James Webb Space Telescope, which may well extend the reach of stellar population work to encompass the full range of the star-forming history of the Universe. However, most of these developments will require extensive advance preparation in order to be used effectively. The time to start that preparation is now (if not yesterday). Three areas which need urgent development are highlighted in these proceedings: (1) We need a wide-field high-resolution spectroscopic capability to augment wide-area imaging surveys; (2) We need a set of AO-friendly extragalactic deep fields in order to exploit upcoming AO-fed instrumentation; and (3) Existing tools for population synthesis modeling need to be extended in order to incorporate the effects of dust. Because the physics of dust creation and destruction is so complicated and uncertain, the latter capability sounds almost impossibly hard to develop, but in this talk I will argue that some simple approaches already exist that allow dust to be injected rather naturally into population synthesis models. I will show a concrete example where incorporation of dust into spectral synthesis models allows one to detect and characterize rate of formation of circumstellar disks at high redshifts.

Keywords. stars: general, stars: AGB and Post-AGB, techniques: spectroscopic, instrumentation: adaptive optics

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1. Future directions: lessons from the JWST science case

This write-up summarizes the conclusions of a talk whose main focus is the future of stellar population work. As we all know, the future is vexingly unpredictable, and one ought to approach all attempts at prognostication with considerable skepticism. Nevertheless, one has to start somewhere, and I thought it might be amusing to structure this talk around NASA's vision for the future in the context of the James Webb Space Telescope (JWST). This mission's projected launch date is mid-2014, so it is now close enough that the project is beginning to dominate both mindshares and budgets. The first question we will try to answer is: 'How does stellar population work figure into the planning for JWST?'.

An interesting perspective on this question is provided in Figure 1. This shows a snapshot of the JWST project's home page, from which we see that the mission's science objectives are structured around four basic themes: (1) First Light; (2) Galaxy formation; (3) Star formation, and (4) Extrasolar planets. A moment's thought suffices to show that stellar population work is directly relevant for the first three themes. The first theme (which is arguably the main driver for the basic design of JWST) is almost entirely focused on stellar populations, since there is an almost Pavlovian conditioning which makes most of us associate ‘First Light’ with ‘Population III’ , even though a number of other plausible possibilities for the sources of reionization exist (such as decaying dark matter). The next two themes are equally straightforward to link with stellar populations: population synthesis is a central tool in modeling galaxy evolution, and star formation is self-evidently relevant to work on stellar populations. A much more surprising conclusion, which is not at all obvious now but which I hope to convince you of by the end of this talk/writeup, is that fourth theme (exoplanets) is also connected with stellar populations. If you eventually buy into this premise, then *stellar population work will be of relevance for every major science theme anticipated for JWST*, which is quite a remarkable testimony to the future importance of the field.

JWST Science

The James Webb Space Telescope (JWST) will be a giant leap forward in our quest to understand the Universe and our origins. The JWST will examine every phase of cosmic history: from the first luminous glows after the Big Bang to the formation of galaxies, stars, and planets to the evolution of our own solar system. The science goals for the JWST can be grouped into four themes:

The End of the Dark Ages: First Light and Reionization seeks to identify the first bright objects that formed in the early Universe, and follow the ionization history.

Assembly of Galaxies will determine how galaxies and dark matter, including gas, stars, metals, physical structures (like spiral arms) and active nuclei evolved to the present day.

The Birth of Stars and Protoplanetary Systems focuses on the birth and early development of stars and the formation of planets.

Planetary Systems and the Origins of Life studies the physical and chemical properties of solar systems (including our own) and where the building blocks of life may be present.

Figure 1. What NASA thinks the future is going to hold. This snapshot of the front portal of the JWST web site was taken in August 2009.

First Light/Reionization is the topic of an entire symposium at this General Assembly (Symposium 265: ‘Chemical Abundances in the Universe - Connecting First Stars to Planets’), and the prospect for immense progress in the next ten years seems obvious. Therefore, to keep this review of manageable size, for the remainder of this writeup/talk I will neglect Population III completely, and focus my attention on the remaining three science themes encapsulated by Figure 1 (galaxy evolution, star formation, and exoplanets).

1.1. *Emerging technologies and planning for future observations*

Progress in astrophysics is so closely linked to progress in technology that when planning for the future it seems obvious to start off by looking for emerging/disruptive technologies and observational campaigns that are on the horizon. We ask ourselves what sets of observations have the potential to be transformed by (and, in turn, to trans-

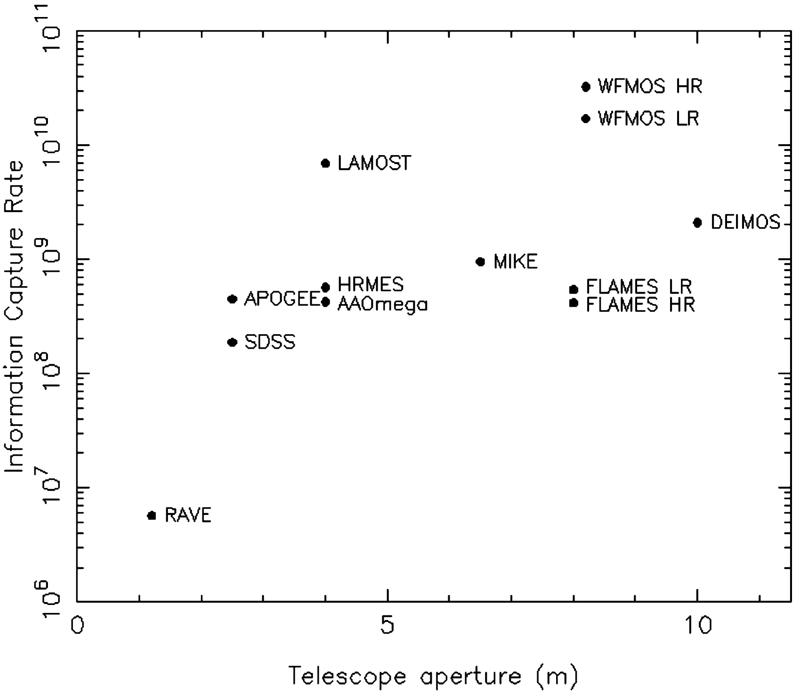

Figure 2. Information capture rate as a function of telescope aperture for various existing and proposed spectrographs. The information capture rate is defined as the number of fibers multiplied by the spectral resolution multiplied by the wavelength coverage multiplied by the area of the mirror multiplied by the efficiency of the spectrograph. A spectrograph capable of undertaking efficient chemo-dynamical programs of 'galactic archaeology' would lie at the upper right of the diagram. (Figure kindly provided by R. Ellis and the WFMOS team).

form) stellar population work over the next decade. Obvious candidates are the ongoing and upcoming wide-field photometric surveys, such as SkyMapper (happening now; see Keller *et al.* 2007 for an overview), Pan-STARRS (happening now; see Kaiser 2004 for an overview), and LSST (first light planned for 2015; see Tyson 2002 for an overview). Wide-area spectroscopic surveys are also going to be extraordinarily exciting, e.g. RAVE (happening now, finished in 2013), Gaia (2012-2020), SDSS SEGUE II (happening now) and APOGEE (2011-2014), BRAVA (completed), LAMOST (starting 2010), 6dF (completed), and large PI programs being undertaken with FLAMES on the VLT (e.g. Tolstoy *et al.* 2004), DEIMOS on the Keck (Koch *et al.* 2006; Ibata *et al.* 2005, Kalirai *et al.* 2006), and MIKE on Magellan (Walker *et al.* 2007, 2008). The ultimate way to tie these datasets together would be to incorporate them into a chemo-dynamical survey of the Galaxy, along the lines of the 'galactic archaeology' program envisioned by Freeman & Bland-Hawthorn (2002), in which stellar population streams are chemically tagged and the formation history of the Milky Way is effectively rewound using N-body simulations. High spectral resolution, relatively large wavelength coverage, and high signal-to-noise are all needed to undertake this ambitious program. The appropriate figure of merit for a spectrograph needed to do the job is the product of the multiplex advantage, spectral resolution, wavelength coverage, aperture, and efficiency of the spectrograph. Figure 2 (kindly provided by R. Ellis) shows the product of all these factors (the 'information capture rate') plotted as a function of telescope aperture, and it is fairly clear that no existing spectrograph is well suited to a project of this scale. For example, a wide-field ~1000 fiber instrument on an 8m-class telescope doing a high-resolution ($R = 20000$) survey to $V < 17$ mag would get abundances for $\sim 10^6$ stars and chemically tag ~ 100 streams in ~ 150 nights (Ellis, personal communication). The spectrograph just described roughly corresponds to WFMOS (a spectrograph proposed for the Subaru telescope), and would inhabit the top right portion of Figure 2. While the anticipated price tag for such an instrument is clearly rather daunting, the prospect of unlocking the formation history of the Milky Way in exquisite detail makes this program hugely attractive in spite of the cost, and it seems achievable in the next decade.

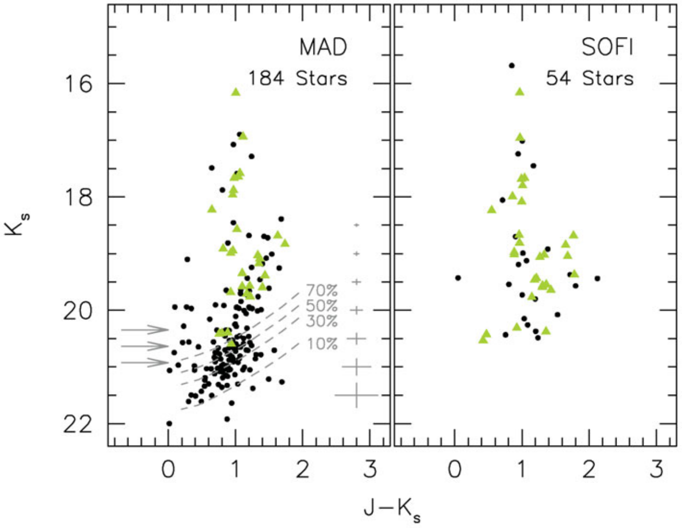

Fig. 2. CMD obtained from MAD data (*left*) and from SOFI data (*right*) for the same FoV. In the left panel, the completeness levels (*dashed lines*) and photometric errors (*crosses*) from artificial star experiments are shown. The expected location of the TRGB is indicated with arrows for [Fe/H] = −1.0, −1.5, and −2.0 (top to bottom). Stars used as secondary photometric standards are shown as triangles.

Figure 3. Figure taken from Gullieuszik *et al.* (2008) who present a color-magnitude diagram of resolved stellar populations in the the nearby dwarf irregular galaxy UKS 2323-326. The figure compares a color-magnitude diagram obtained using the ESO Multi-Conjugate Adaptive Optics Demonstration facility (on the left) with a corresponding color-magnitude diagram obtained in good natural-seeing conditions (on the right). Note both extraordinary depth of the AO-assisted color-magnitude diagram, as well as the capability of multi-conjugate AO to extend AO observations down to the J-band.

1.2. *Planning for near-field cosmology and galactic archaeology*

Unlocking the formation history of the Milky Way using chemo-dynamical investigations of stellar populations would seem to be the first step in a broader campaign of ‘near field cosmology’ whose logical extension would be complementary analyses of nearby galaxies. At first glance, it seems that improvements in spatial resolution from adaptive optics is set to transform this field (see the color-magnitude diagram, taken from Gullieuszik *et al.* 2008, for the nearby dwarf irregular galaxy UKS 2323-326 presented in Figure 3 for an example). However, we now run up against a roadblock, because for the foreseeable future such work must all be undertaken in the near infrared, while most diagnostic lines and spectral breaks lie at visible wavelengths (or in the UV). As has been emphasized by Tolstoy and others in these proceedings, a combination of visible and NIR colors provides a path forward, though NIR colors on their own do not provide much information for most stars (with certain exceptions, such as for the TP-AGB phase). This is a prime example of future progress requiring careful planning now, because the image quality of JWST blueward of about 1μm may not be very good, so visible-wavelength photometry at high resolution must be obtained now, before the demise of HST. The ANGST program (see Dalcanton's contribution to these proceedings) is a good example of an essential HST program currently being undertaken that will give future extremely large telescopes something to build on.

1.3. *Planning for far-field cosmology with adaptive optics*

The need for careful planning now in order to exploit future advances made possible by adaptive optics is even more evident when we move from the 'near-field cosmology' of resolved stellar populations to the 'far-field cosmology' of the distant Universe. Our understanding of the high-redshift universe has been revolutionized by the various HST deep fields, such as the HDF, UDF, GOODS, COSMOS, etc., several of which have been extensively surveyed at all accessible wavelengths. The best compendium of the data available for all existing deep fields is Jarle Brinchmann's on-line summary, which at the time of this writing is located at:
`http://www.strw.leidenuniv.nl/~jarle/Surveys/DeepFields/index.html`

Stellar population work at high-redshifts in these deep fields focuses on the analysis of the morphological and kinematical sub-components of galaxies (e.g. the disk and the bulge), but because galaxies at such high redshifts are typically $<$ 1 arcsec in size, kinematical investigations require adaptive optics spectroscopy. The promise of such observations has been held out as an exciting next step for many years (see, for example, the many references in van Breugel & Bland-Hawthorn 2000). Unfortunately, it is now clear that only very limited AO observations are going to be undertaken in any existing deep field.

The basic problem with undertaking AO in existing HST deep fields is that, even with a laser guide star-based system, one still needs a reasonably proximate natural guide star to supply the information needed for tip-tilt correction. On the other hand, two of the main selection criteria when identifying deep fields have been that they contain as few bright stars as possible to avoid saturation in long exposures, and that they lie in regions of low Galactic extinction. Thus all existing deep fields are near the Galactic poles, where the density of suitable guide stars is at a minimum. For example, Davies *et al.* (2007) report that only 1% of the Lyman break galaxy sample of Mannucci (2007) are accessible to the VLT laser guide star system, after suitable color cuts and elimination of systems at redshifts obscured by strong OH features. The situation is similar with Gemini, whose AO system has similar sky coverage. Even with the next-generation Gemini Multi-Conjugate AO system (MCAO), the H-band sky coverage at the galactic poles will only be around 15%, and the system will have very marked improvement in mean Strehl ratio in fields where more than the minimum number of natural guide stars are available. This is because the geometry of the guide stars on the sky impacts the uniformity of Strehl (Flicker & Rigaut 2001).

One way forward has been suggested by Damjanov *et al.* (2009), who proposes that 'AO-friendly' patches on the sky be developed in order to allow efficient AO-based

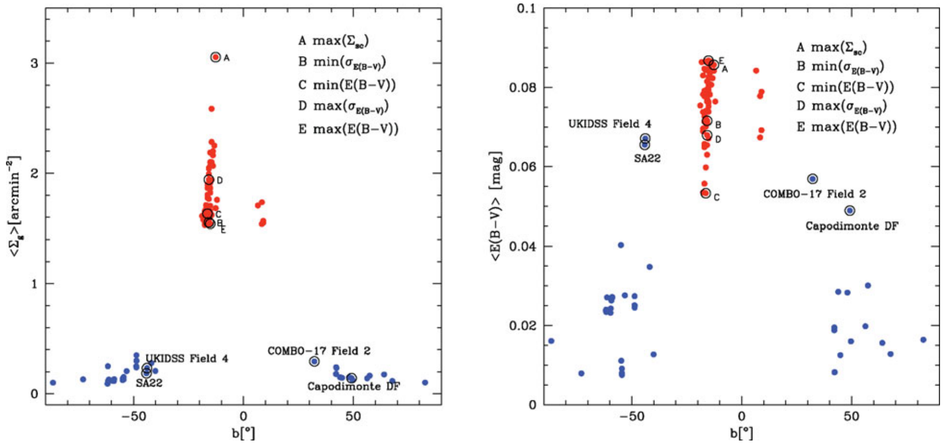

Figure 4. Reddening coefficient $E(B-V)$ as a function of the star counts surface density $\Sigma_{\rm sc}$ for 165 one square degree fields with $\Sigma_{\rm sc} > 0.5$ arcmin^{-2} and $E(B-V) \leqslant 0.1$. The fields are color-coded based on their equatorial coordinates. The fields flagged with open circles have the highest star counts surface density or lowest standard deviation of the reddening coefficient. Colored arrows point at the representative fields for each of the three sightlines. (Figure taken from Damjanov et al 2009).

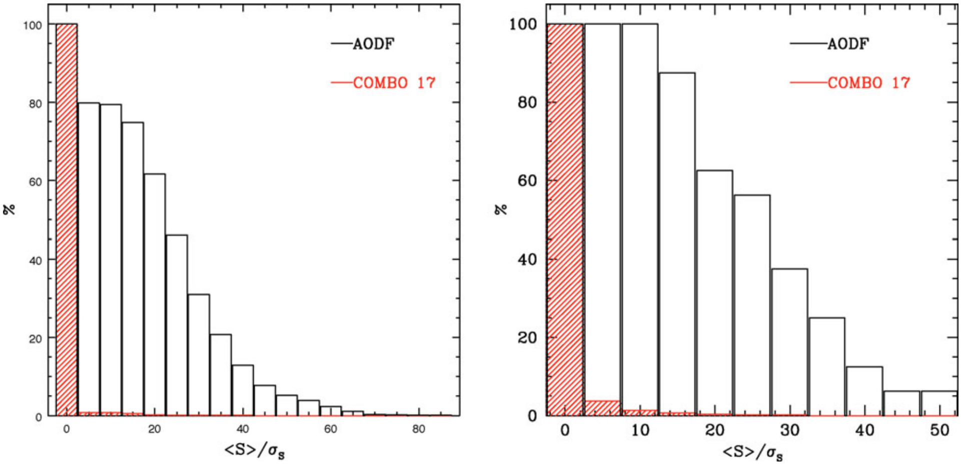

Figure 5. The cumulative distribution of a Strehl-related figure of merit for the AO-optimized extragalactic field presented in Damjanov *et al.* 2009 (shown in black) and for the COMBO 17 Field 2 (shown in red). The figure of merit is simply S/σ where S is the best Strehl ratio achieved, and σ is the RMS variation in Strehl over a fixed area. The data points are are binned according to their FoM value in 5 (units) wide bins. The vertical axis gives the percentage of the field area with the FoM value equal or higher than the lower limit of the corresponding bin. The left panel correspond to a natural guide star magnitude limit of 16.5 mag in R-band and a bright sky; the right panel presents the case of fainter natural guide star magnitude limit (18.5 mag in R) and dark sky. See Damjanov *et al.* (2009) for details.

extragalactic observations to be undertaken in the future. These authors identify a number of patches on the sky which have the rare combination of both high stellar surface density ($\geqslant$0.5 arcmin^{-2}) and low extinction ($E(B-V) \leqslant 0.1$). Figure 4 presents a comparison of the stellar density and extinction in some of the Damjanov *et al.* fields to those in a set of existing HST deep fields, with the basic conclusion being that the proposed fields typically have over ten times the stellar density of existing deep fields coupled with

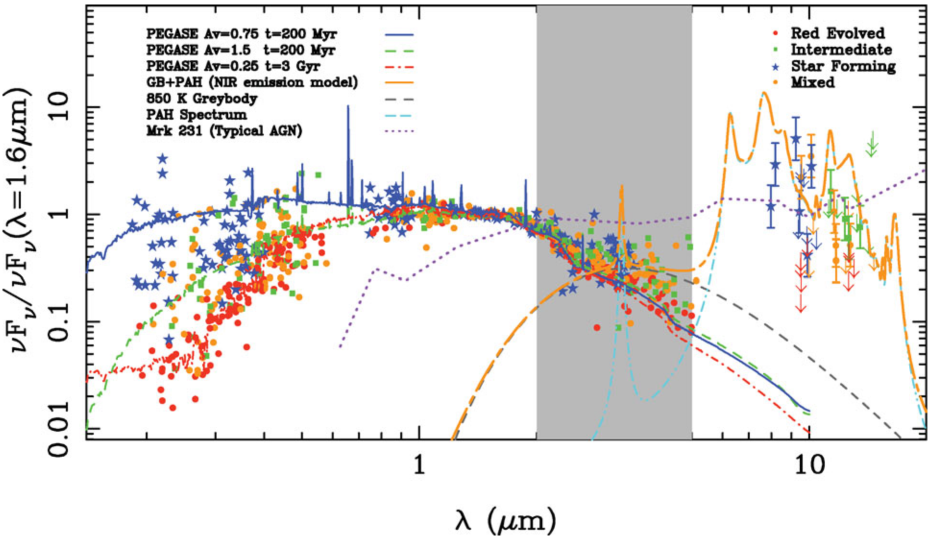

Figure 6. Figure taken from Mentuch *et al.* (2009) showing VIzK$_s$+IRAC and MIPS photometry from the galaxies in the Gemini Deep Deep Survey, normalized at $\lambda = 1.6\,\mu$ with the 2-5 μ region of NIR excess highlighted in gray. Plot symbols are keyed to galaxy spectral type, as shown in the legend. The blue solid curve is a stellar component model from PEGASE.2 for a typical star-forming galaxy (t = 200 Myr, A$_v$ = 0.75). A dusty star-forming galaxy (t = 200 Myr, A$_v$ = 1.5) and evolved galaxy (t = 3 Gyr; A$_v$ = 0.25) are also plotted. The orange dash-long–dashed line represents the NIR emission component model (GB+PAH) from da Cunha *et al.* (2008) that is supplemented in the SED modeling. An 850 K graybody emitter (gray dashed line) contributes most of the emission of this component at 2-5 μ, although the 3.3 μ PAH feature (the cyan dot-dashed curve) has some contribution (< 20 % in a given IRAC band). For reference, an SED of an AGN (Mrk 231; purple dotted curve) is plotted. For pedagogical purposes, the GB+PAH and AGN curves have been normalized to the average MIPS flux of the sample. For those objects with MIPS detections, the AGN model is not a good representation of the photometry)

extinction values at the high end of those in existing deep fields. How this translates into practical performance benefits is presented in Figure 5, in which a multi-conjugate adaptive optics simulator has been used to compute the distribution of a figure of merit (a combination of peak strehl ratio and uniformity in strehl; see figure caption) in one of the proposed fields, as well as in an existing deep field (COMBO-17). The improvement in efficiency obtained by undertaking AO in the preferred field is astonishing.

2. 'Embracing and extending' dust models

In the final portion of this talk I would like to focus on future directions for models, with a focus on those models which seem complementary to the observations described in the previous section. Some beautiful talks at this meeting have already described the current state-of-the art, impending improvements, and remaining challenges in population synthesis (see, for example, contributions by J. Brinchmann, C. Leitherer, G. Bruzual and S. Charlot). Since I am merely a user (as opposed to a developer) of these codes, I cheerfully defer to my colleagues for predictions about future technical improvements in the models. I would instead like to focus on the 'big picture' applicability of the models to a broader class of problems. In particular, I would like to explore the idea that a natural goal for future modeling will be to extend them to incorporate contributions from dust.

I am driven to this conclusion because the natural trajectory of future observations is toward longer wavelengths. At the same time, I am aware of the many difficulties in

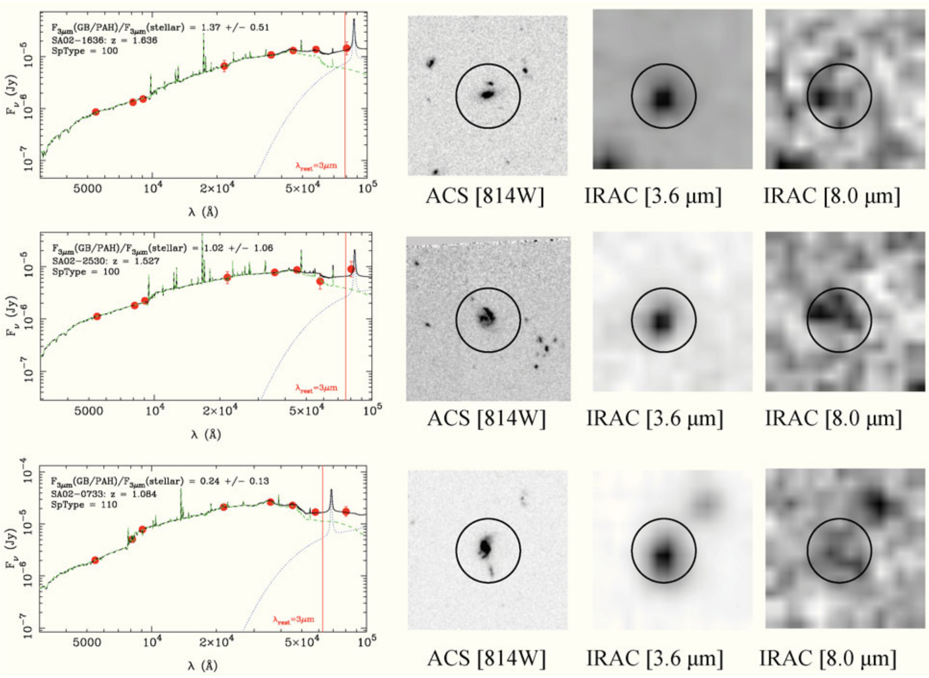

Figure 7. Figure taken from Mentuch *et al.* 2009 showing spectral energy distribution fit examples for objects (band fluxes shown as red dots) with SFRs $> 1\,M_{\odot}$/yr. The SED (solid black line) is composed of both a stellar component (green dashed) and an NIR emission component consisting a 850 K graybody emission and a PAH spectrum (blue dotted line). 10 arcsec postage stamps from *Hubble's* ACS [814W], IRAC [3.6μ] and [8.0μ] are shown for each object. The spectral type of the galaxy is given in the top left corner showing the excess is seen in star-forming, intermediate, and mixed population galaxies. For reference, $\lambda_{\rm rest} = 3\,\mu$ is plotted as a red vertical line. The black circles show the 4 arcsec apertures used to derive our photometry.

modeling dust, and recognize that the uncertain physics of dust production and destruction makes modeling dust in any detail a huge challenge. At the same time, I think we should recognize that there is some scope for incorporating dust into models in a number of fairly simple ways, and that we really ought to be doing this already, if only for the sake of consistency.

For example, most models treat dust extinction in the UV and dust emission in the infrared independently. There are a few notable exceptions, such as the *Sunrise* models of Jonsson (2006) described by C. Hayward in these proceedings, and the work presented by R. Riffel in these proceedings (and also in Riffel *et al.* 2009) using the *STARLIGHT* code (Cid Fernadez *et al.* 2004; Mateus *et al.* 2006; Asari *et al.* 2007; Cid Fernandez *et al.* 2008). But on the whole most modeling work does not use the mid-infrared properties of galaxies to inform the choice of the UV extinction curve being used, despite the energetic connection between these components. At a very basic level, which is all I am really advocating we consider here, there is really no excuse for this. We have known for nearly 20 years (since the classic paper of Désert, Boulanger and Puget 1990) that the big grains responsible for the linear rise in the near-UV spectral slope are also responsible for the thermal far-IR emission, and that the polycyclic aromatic hydrocarbon molecules responsible far-UV non-linear UV extinction are also responsible for the mid-IR emission lines, and also that whatever mysterious grains are responsible for the 2175Å bump in the UV extinction curve also correspond to an additional component in the mid-IR

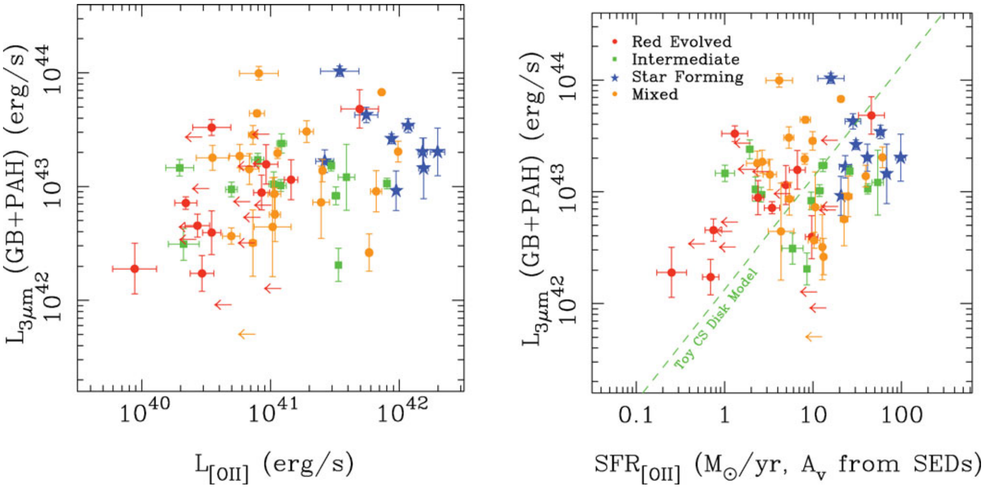

Figure 8. A figure (from Mentuch *et al.* 2009) showing the luminosity of the 3μm excess (modeled as a graybody+PAH component) is correlated ($r = 0.49 \pm 0.06$) with the [OII] line luminosity (left panel) and the star-formation rate (right panel). The dashed green line is the luminosity expected from an NIR excess due to circumstellar disks (that last for 1 Myr) in massive star forming regions, assuming a simple model that scales linearly with the SFR (Mentuch *et al.* 2009 for details). The total luminosity of this model matches the galaxy's total luminosity in the NIR. Galaxies are indicated by spectral types as star-forming (blue stars), evolved (red circles), intermediate (green squares), and mixed (orange circles).

emissivity peaking at around 60μm. Knowing this, there is no reason why the mid-IR properties of galaxies ought not be used to place some basic constraints on the choice of UV extinction curve, at least at the simple level of putting limits on the far-UV slope and on the strength of the 2175Å bump.

I believe that incorporating dust into spectral synthesis models can yield some interesting surprises. A nice example of this is given in an investigation led by my student Erin Mentuch (Mentuch *et al.* 2009), who looked at the UV/Visible/NIR/Mid-IR colors of 88 $0.5 < z < 2$ galaxies taken from the Gemini Deep Deep Survey (Abraham *et al.* 2004). Detailed modeling of these colors (see Figure 6) shows clear evidence for a near-infrared excess at around $3\,\mu$m, which at the redshifts of these galaxies is seen in the IRAC [$5.8\,\mu$m] and [$8.0\,\mu$m] bands. The excess can be modeled as an additional SED component consisting of a modified 850 K graybody augmented with a mid-IR PAH emission template spectrum, as suggested by da Cunha *et al.* (2008). The luminosity of the excess SED component is correlated with the star-formation rate of the galaxy, so the excess shows some promise as an extinction-free star formation tracer. Hints that the excess is correlated with star-formation activity and morphology can be seen in HST imaging data (e.g. the examples shown in Figure 7). But the main interest of the excess lies in the interpretation of its origin, which Mentuch *et al.* (2009) attribute to the collective emission from the thousands of circumstellar disks around massive stars in these galaxies at high redshifts. As Figure 8 shows, coupling the predictions from a simple flared disk model to the star-formation rates determined from the SED model fits and [OII] emission does a surprisingly credible job of explaining the excess emission. All other candidates for the excess emission require unrealistic abundances or extremely high duty cycle star formation. It seems natural to suppose that the presence of circumstellar disks around massive stars at high redshifts would also imply the presence of disks around less massive stars, and of course it is around these less massive systems that we would expect planets to form. Therefore this 3 μm excess presents us with an opportunity to probe the formation of planets (as seen in their total integrated light) at cosmic epochs even before our own Solar System formed.

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