First Results from the SPICES Survey

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Abstract. We present first results from SPICES, the Spectroscopic, Photometric, Infrared-Chosen Extragalactic Survey. SPICES is comprised of four \(\approx 30\) arcmin\(^2\) high Galactic latitude fields with deep \(BRIzJK_s\) imaging reaching depths of \(\approx 25\) mag (AB) in the optical and \(\approx 23\) mag (AB) in the near-infrared. To date we have 626 spectroscopic redshifts for infrared-selected SPICES sources with \(K_s < 20\) (Vega). The project is poised to address galaxy formation and evolution to redshift \(z \approx 2\). We discuss initial results from the survey, including the surface density of extremely red objects and the fraction of infrared sources at \(z > 1\). One of the SPICES fields has been the target of a deep 190 ksec \textit{Chandra} exposure; we discuss initial results from analysis of that data set. Finally, we briefly discuss a successful campaign to identify high-redshift sources in the SPICES fields.

1 Introduction

The past few years have been a watershed in our ability to directly observe galaxy evolution. Deep field surveys such as the Canada-France Redshift Survey (CFRS – Lilly et al. 1995) and color-selected field samples such as that of Steidel et al. (1996, 1999) have provided critical information on the evolution of field galaxies. Madau et al. (1996) integrated the results at \(z < 5\) into a coherent picture of the star formation history of the Universe, suggesting that the global star formation rate peaked between \(z = 1\) and 2. Since then, recognition of the importance of both dust and cosmic variance has changed the steep decline in the cosmic star formation rate inferred at \(z > 2\) into a flat plateau for \(1 \lesssim z \lesssim 4\) (Steidel et al. 1999). Cowie et al. (1999) also show a more gradual rise at \(z < 1\) than initially inferred by the CFRS.
There remain four substantial caveats regarding these findings. First, the number of spectroscopically measured redshifts between $z = 1$ and 2 is small. Second, since the UV dropout technique used to identify the $z \gtrsim 3$ population requires them to be UV bright, it is possible that a substantial amount of star-forming activity in dusty systems has been overlooked. Third, redshift surveys from which cosmic star formation rates are measured must be of sufficient depth and wavelength coverage that star formation indicators (e.g., $M(2800 \, \text{Å})$) can be measured with limited extrapolation over wide redshift intervals. Finally, small area surveys, such as the HDF, are vulnerable to perturbations from large scale structure.

Infrared-selected surveys provide a powerful tool for addressing these issues (e.g., see Dickinson, these proceedings). Among the benefits, infrared $k$-corrections are small and relatively independent of galaxy type, age, and redshift. Since the long-wavelength light of galaxies is dominated by lower mass stars rather than short-lived high-mass stars, infrared luminosities track galaxy mass, thereby providing a more direct comparison to theories of galaxy formation without relying on the poorly-understood physics of star formation. Infrared light is also less vulnerable to dust absorption.

On the negative side, since spectroscopy is primarily performed at optical wavelengths, infrared-selected samples are challenging to follow-up. Also, since evolved stars become important contributors to the long-wavelength flux of a galaxy, poorly-understood phases of stellar evolution can make interpretation of broad-band colors ambiguous (e.g., Spinrad et al. 1997). Finally, since infrared-surveys do not select for young stars, they are suboptimal for studying the cosmic star-formation history, though they provide a natural basis for studying the mass-aggregation history.

## 2 First Results from SPICES

We present the SPICES survey (Eisenhardt et al. 2001, in prep.), a deep $BRIzJK_s$ imaging and spectroscopic survey covering over 100 arcmin$^2$ spread over four fields. Table 1 lists the Vega magnitude 3σ depths in 3″ diameter apertures for the imaging. The relatively large area mitigates the effects of large-scale structure while the $K$-band depth is more than sufficient to detect $L^*$ galaxies to $z = 2$. The area and depth are a significant improvement over several recent surveys (e.g., Cowie et al. 1996), but are modest compared to several programs currently in production mode (e.g., Cimatti, these proceedings; McCarthy, these proceedings). An important strength of SPICES is the spectroscopic program: we currently have 626 spectroscopic redshifts of $K < 20$ sources selected from the sample, approximately one-third of the complete $K < 20$ sample (see Figure 1). These spectroscopic redshifts are being used to directly construct an eigenbasis of galaxy spectral energy distributions with which to determine photometric redshifts for the complete sample (see Budavari et al. 2000). Wu et al. (these proceedings) discusses
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Fig. 1. Status of the current survey. We now have 626 spectroscopic redshifts over the four fields which comprise the survey. Left: Location of the spectroscopic redshifts in $K - z$ space. Filled-in circles indicate unambiguous redshifts, while open circles indicate likely redshifts. Note the vertical stripes corresponding to large scale structures at several redshifts between $z \approx 0.6$ and $z \approx 1.3$. Right: Location of SPICES sources in color-magnitude space. Dots correspond to objects lacking spectroscopic redshifts. Symbols indicate redshift for spectroscopic targets. Note that $I - K > 4$ is a robust indicator of $z > 1$.

HST imaging of one of the SPICES fields. Here we discuss two initial results from the survey.

Table 1. Depth of SPICES Imaging (Vega magnitudes)

| filter | $B$  | $R$  | $I$  | $z$  | $J$  | $K_s$ |
|--------|------|------|------|------|------|-------|
| 3σ depth | 27   | 25.5 | 25.0 | 24.2 | 23.0 | 21.3  |

The Surface Density of ERO’s: Extremely red objects (ERO’s) are an intriguing class of extragalactic object, likely associated with $z \gtrsim 1$ galaxies (e.g., Cimatti, these proceedings). We find that the surface density of these sources is elevated in the SPICES fields relative to some of the surface densities reported previously in the literature. For $I - K < 4$, $19 < K < 20$, we find a surface density of $1.4$ ERO’s arcmin$^{-2}$, with a range in this value of $1.3$ to $1.9$ across the four fields. For the same magnitude range and color criterion, Barger et al. (2000) find a surface density of $0.2 \pm 0.1$ ERO’s arcmin$^{-2}$ over a field of view of $61.8$ arcmin$^2$ while McCracken et al. (2000) find a surface density of ERO’s in the Herschel Deep Field of $0.5 \pm 0.1$ arcmin$^{-2}$ over a 47.2 arcmin$^2$ field. Similarly, if we consider ERO’s defined as $K < 19$ sources with $R - K > 6$, the SPICES fields have $0.13$ ERO’s arcmin$^{-2}$ with a range of $0.06 - 0.32$ ERO’s arcmin$^{-2}$ across the four fields. Using the same definition, the CADIS survey finds $0.039 \pm 0.016$ ERO’s arcmin$^{-2}$ across a
154 arcmin$^2$ field (Thompson et al. 1999) while Daddi et al. (2000) find 0.07 ERO's arcmin$^{-2}$ across a 447.5 arcmin$^2$ field with strong clustering reported. What is the source of this discrepancy? One possibility is that the depth and area of the SPICES imaging are significantly improved over many of the surveys mentioned above: $K = 20$ is a 10σ detection in the SPICES survey. Another possibility is large scale structure. Though the SPICES fields cover > 100 arcmin$^2$, larger than several of the above surveys, fluctuations in the ERO surface density on these scales have been reported by more recent larger area deep infrared surveys (e.g., Daddi et al. 2000; Cimatti, these proceedings; McCarthy, these proceedings). Indeed, one of the SPICES fields (the Lynx field: 08$^h$48$^m$, +44°54′) has a higher surface density of red objects than the other three fields. Keck/LRIS spectroscopy has subsequently identified many of these red sources with galaxies in two X-ray emitting clusters at $z \sim 1.27$ (Stanford et al. 1997; Rosati et al. 1998).

The $z > 1$ Fraction: The $K$-band luminosity function (KLF) at $z = 1$ offers a powerful constraint on theories of galaxy formation. Since the $K$-band light tracks mass better than ultraviolet/optical light, the KLF is more directly comparable to theories of the collapse and merging of galaxies. Kauffmann & Charlot (KC98; 1998) show that pure luminosity evolution (PLE) models, i.e., models in which galaxies collapse monolithically at high redshift with little subsequent merging activity, predict that many massive galaxies exist at $z = 1$: $\approx 54\%$ of an infrared-selected field galaxy sample with $18 < K < 19$ should be at $z > 1$. Alternatively, their hierarchical model predicts only $\approx 3\%$ of $18 < K < 19$ field galaxies should be at $z > 1$. Ignoring the SPICES field with the $z \sim 1.27$ clusters and another field with very limited spectroscopy, we conservatively find that $> 17\%$ of $18 < K < 19$ SPICES sources are at $z > 1$. This assumes that $\approx 67\%$ of $K < 19, I - K > 4$ (i.e., red) sources are at $z > 1$, as our spectroscopic program shows thus far, and we only count those $18 < K < 19, I - K < 4$ (i.e., blue) sources already spectroscopically confirmed to be at $z > 1$. Early photometric redshift analysis on these fields suggests a value $\approx 25\%$ of the $18 < K < 19$ being at $z > 1$. These numbers show that neither PLE nor the KC98 hierarchical model correctly predicts the $z \approx 1$ KLF, implying that substantial merging occurs at $z > 1$.

3 X-Ray SPICE and High-z SPICE

The identification of two clusters at $z \sim 1.27$ and one cluster at $z = 0.56$ in the Lynx SPICES fields has led to a deep, 190 ksec Chandra map of the field. Analysis of the diffuse high- and low-redshift cluster X-ray emission are discussed in Stanford et al. (2001, submitted) and Holden et al. (2001, in prep.), respectively. Stern et al. (2001, in prep.) discusses X-ray background (XRB) results from this data set. We confirm results of recently published Chandra studies (e.g., Giacconi et al. 2001): most of the 0.5 – 10 keV XRB is resolved into discrete sources; the fainter soft-band sources have harder
X-ray spectra, providing a coherent solution to the long-standing ‘spectral paradox’; and \( \approx 90\% \) of the sources have optical/near-infrared identifications in deep ground-based imaging. A preliminary spectroscopic program shows a mix of obvious AGN, apparently normal galaxies, and, perhaps surprisingly, several X-ray emitting stars, some with hard X-ray spectra.

We are also targeting the SPICES fields with very deep imaging in \( RIZ \) to identify high-redshift sources using the Lyman break technique. This work has led to the discovery of a faint quasar at \( z = 5.50 \) (Stern et al. 2000) and several high-redshift galaxies out to \( z = 4.99 \). Strong emission-line galaxies have also been identified serendipitously during the SPICES spectroscopic campaign, the highest redshift source being a likely \( z = 5.17 \) Ly\( \alpha \) emitter with \( f_{\text{Ly}\alpha} \approx 9 \times 10^{-17} \text{ erg cm}^{-2} \text{ s}^{-1} \).

4 Conclusions

We present first results from the SPICES survey, an infrared-selected photometric and spectroscopic survey. We find an elevated surface density of ERO’s compared to several recent deep, infrared surveys, likely due to fluctuations in that quantity from large scale structure at moderate redshifts. Perhaps relatedly, we also find a large fraction of infrared-bright \( (K < 19) \) galaxies residing at \( z > 1 \). A good measure of this quantity provides a powerful constraint on models of galaxy formation.

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