THE FLAMINGOS EXTRAGALACTIC SURVEY

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ABSTRACT

Using the Florida Multi-object Imaging Near-IR grism Observational Spectrometer (FLAMINGOS), we have conducted the FLAMINGOS Extragalactic Survey (FLAMEX), a deep imaging survey covering 7.1 deg2 within the 18.6 deg2 NOAO Deep Wide-Field Survey (NDWFS) regions. FLAMEX is the first deep, wide-area near-infrared survey to image in both the J and Ks filters, and is larger than any previous NIR surveys of comparable depth. The intent of FLAMEX is to facilitate the study of galaxy and galaxy cluster evolution at 1 < z < 2 by providing rest-frame optical photometry for the massive galaxy population at this epoch. This effort is designed to yield a public data set that complements and augments the suite of existing surveys in the NDWFS fields. We present an overview of FLAMEX and initial results based upon ~ 150,000 Ks-selected sources in the Boötes field. We describe the observations and reductions, quantify the data quality, and verify that the number counts are consistent with results from previous surveys. Finally, we comment upon the utility of this sample for detailed study of the ERO population, and present one of the first spectroscopically confirmed z > 1 galaxy clusters detected using the joint FLAMEX, NDWFS, and Spitzer IRAC Shallow Survey data sets.

Subject headings: surveys — infrared: galaxies — galaxies: evolution — galaxies: clusters

1. INTRODUCTION

Two fundamental goals of extragalactic astronomy are to understand the star formation and mass assembly histories of the universe. It has become increasingly apparent in the last few years that the epoch z = 1 − 2 is critical for the evolution of both quantities. Current observations indicate that the bulk of stellar mass assembly in galaxies and ~ 50% of the total star formation occurs in this interval (Fontana et al. 2003; Dickinson et al. 2003; Rudnick et al. 2003). It is also during this epoch that we expect to witness the formation of the first massive galaxy clusters (for example, see Haiman et al. 2001). Observations at this epoch thus promise to provide a portrait of the universe during its most vibrant evolutionary period. Yet, in contrast to the wealth of data at low redshifts, this epoch is critical for the evolution and clustering of the massive galaxy population at z = 1 − 2 and to identify a sample of galaxy clusters at this epoch that can be used to study the assembly of cluster galaxies. The NDWFS fields are the targets of one of the most extensive panchromatic investigations in all astronomy, with space- and ground-based imaging and spectroscopic programs spanning radio to X-ray wavelengths (Jannuzi & Dey 1999; Rhoads et al. 2000; de Vries et al. 2002; Hoopes et al. 2004; Lonsdale et al. 2003; Eisenhardt et al. 2004; Kochanek et al. 2004; Pierre et al. 2004; Houck et al. 2005; Murray et al. 2005). The northern (Boötes) field in fact is the only wide-area survey region presently mapped by Chandra, GALEX, and Spitzer (with IRAC and MIPS).

FLAMEX provides a combination of area and depth in both J and Ks that is unique among current NIR surveys (see Table 1 and Figure 1). Coupling the FLAMEX data with the optical (and when available IRAC) photometry enables derivation of robust photometric redshifts (Brodwin et al., in prep., and Brown et al., in prep.), providing an efficient means of isolating large samples of massive galaxies at z = 1 − 2. This combination of mass selection and photometric redshifts over a wide area constitutes a powerful tool not only for galaxy...
We note that different authors quote different significance limiting magnitudes (for example, 3σ vs. 5σ) within different size apertures, so the listed values provide only an approximate comparison of survey depths.

This survey is split between two regions with limiting magnitudes of \( K = 23.1 \) and \( K = 23.7 \).

Second, the addition of FLAMEX to the NDWFS repertoire provides the requisite deep NIR photometry that will be required by the next generation of NIR spectrographs. The astronomical community is poised to enter a new era in cluster detection and galaxy evolution studies, but also for selection of subsamples of rare objects that can be studied in greater detail.

The layout of this paper is as follows. We begin by describing the experimental design and observations in \( \S 2 \) including target sensitivities and field geometry. In \( \S 3 \) we present the reduction procedure, followed by a description of the properties of the final Boötes catalog in \( \S 4 \). Illustrations of initial science and a discussion of the data release are given in \( \S 5 \) and the paper is summarized in \( \S 6 \). When relevant we assume a standard cosmology with \( \Omega_M = 0.27, \Omega_{\Lambda} = 0.73, \) and \( H_0 = 70 \) km s\(^{-1}\) Mpc\(^{-1}\).

## 2. Experimental Design and Observations

This survey is made possible by the FLorida Multi-object Imaging Near-Infrared Grism Observational Spectrometer (FLAMINGOS), which when commissioned was the world’s first cryogenically cooled multi-object infrared spectrograph (Elston et al. 2003). FLAMINGOS has a fast all-refractive optical system that can be used at telescopes slower than f/7.5. This optical system, coupled with a \( 2048 \times 2048 \) HgCdTe HAWAII-2 array, makes FLAMINGOS a very efficient wide-field imager when used on fast, small aperture telescopes. For the FLAMEX survey we rely purely on FLAMINGOS’ imaging capabilities and the wide field afforded by the Kitt Peak National Observatory 2.1m. At this telescope FLAMINGOS has a \( 21' \times 21' \) field-of-view with 0.61” pixels.

### 2.1. Location and Field Geometry

We initially targeted rectangular 5 deg\(^2\) regions within each of the two NDWFS fields. The FLAMEX survey chose the NDWFS fields due to the deep optical imaging that was in progress in these fields when the survey was begun, with the \( B_0RI \) data being essential for enabling derivation of accurate photometric redshifts. The even split between the two fields was designed to permit follow-up observations during both observing semesters and from both hemispheres, while still yielding coverage for large, contiguous regions. Finally, the angular size of the survey is driven by the requirement that we probe a sufficiently large volume to detect massive clusters at \( z > 1 \). For a standard \( \Lambda CDM \) cosmology, one expects a

### Table 1. NIR Surveys

| Survey       | Filter | Area (deg\(^2\)) | Depth |
|--------------|--------|-----------------|-------|
| Skrutskie et al. (1997, 2MASS) | JHK\(_s\) | All Sky | \( K = 14.5 \) |
| Gardner et al. (1996) | \( K \) | 9.84 | \( K = 15.6 \) |
| Jannuzi & Devany (1999, NDWFS Boötes) | \( K \) | 9.3 | \( K = 18.6 \) |
| Huo et al. (1997) | \( K' \) | 8.23 | \( K' = 16 \) |
| FLAMEX\(^a\) | \( K_0 \) | 7.1 | \( K_0 \approx 19.3 \) |
| Chen et al. (2002, LCIRS) | \( H \) | 1.1 | \( H \approx 21.5 \) |
| Drory et al. (2001, MUNICS) | \( K' \) | \( K' \approx 19.5 \) |
| Kümmler & Wagner (2001) | \( K \) | 0.91 | \( K = 17 \) |
| Szokoly et al. (1998) | \( K_0 \) | 0.6 | \( K_0 = 16.5 \) |
| Huo et al. (2001, CADIS) | \( K' \) | 0.2 | \( K' = 19.75 \) |
| Daddi et al. (2000) | \( K_0 \) | 0.19 | \( K_0 = 18.5 \) |
| Glazebrook et al. (1994) | \( K \) | 0.12 | \( K = 19.5 \) |
| Cristóbal-Hornillos et al. (2003) | \( K_0 \) | \( 5 \times 10^{-2} \) \( K_0 = 21 \) |
| Minezaki et al. (1998) | \( K' \) | \( 5 \times 10^{-2} \) \( K' = 19 \) |
| Martini (2001) | JHK | \( 3.4 \times 10^{-2} \) \( K = 18.5 \) |
| Cimatti et al. (2002, K20) | \( K_0 \) | \( 1.4 \times 10^{-2} \) \( K \gtrsim 20 \) |
| McLeod et al. (1995) | \( K \) | \( 5.6 \times 10^{-3} \) \( K = 20 \) |
| Totani et al. (2001) | \( K' \) | \( 1.1 \times 10^{-3} \) \( K' = 23.5 \) |
| Djevovič et al. (1995) | \( K \) | \( 8.3 \times 10^{-4} \) \( K = 24 \) |
| Moustakas et al. (1997) | \( K \) | \( 5.6 \times 10^{-4} \) \( K \approx 23.4^a \) |
| Bershady et al. (1998) | \( JK \) | \( 4.2 \times 10^{-4} \) \( K = 24 \) |

**Note.** This table is intended to be a representative rather than a comprehensive synopsis of previous surveys. The surveys are listed in order of decreasing survey area. We note that different authors quote different significance limiting magnitudes, so the listed values provide only an approximate comparison of survey depths.

\( \^a \)This survey is split between two regions with limiting magnitudes of \( K = 23.1 \) and \( K = 23.7 \).
surface density of approximately 0.7−4 deg⁻² clusters with M > 10¹¹ M☉ at z > 1, depending upon the value of $σ_z$. Consequently, the survey must cover roughly 5–10 deg² to ensure detection of a sample of massive clusters at this epoch.

While the survey plan called for a total of 10 deg², in practice worse than expected weather (see below) limited the total coverage to 7.1 deg². In the northern (Boötes) field the survey covers a 4.7 deg² region in both J and $K_s$; in the southern field (Cetus) the corresponding coverage is 2.4 deg². The final geometry of each field is shown in Figures 2 and 3. In Cetus, this geometry was driven by following considerations. First, we started with observations in the eastern part of the NDWFS field to best complement the shallower $K_s$-band imaging from the NDWFS survey (Dey et al., in prep.), which predominantly lies in the western part of the Cetus NDWFS field. Second, we attempted to both maximize overlap with the Spitzer Wide-Area Infrared Extragalactic Survey (Lonsdale et al. 2003, SWIRE), which overlaps with the eastern part of the NDWFS, and cover the Gemini Deep Deep Survey’s (Abraham et al. 2004, GDDS) field in Cetus. The former provides valuable additional information for photometric redshifts and constraining galaxy populations at $z > 1$, while the latter provides calibration for photometric redshifts in the redshift desert ($z ≈ 1.5–2$). Observations were conducted as a gridded series of pointings, with adjacent field centers separated by 20′.

2.2. Survey Specifications

The original technical specifications for the program prescribed imaging of the survey region in both J and $K_s$ for 2 hours to reach depths of $J = 22$ and $K_s = 20.5$ (5σ, Vega) within 2′ diameter apertures, assuming 1.5′′ FWHM seeing.

which for a point source is equivalent to total magnitudes $J = 21.4$ and $K_s = 19.9$. The final catalog is shallower (see Equation 4) due to both the instrumental aberrations and worse than expected image quality. The effective depth of the data are of course also a strong function of the ambient temperature (i.e. the sky brightness). We therefore initially imaged each field for two hours per filter, and then reimaged the shallower fields in later runs to obtain relatively uniform data.

2.3. Observing Procedure

The standard observing sequence for the survey consisted of a randomly ordered 5 × 5 dither pattern, with $I'$ offsets about the pointing center. This pattern was repeated until the required total exposure time was achieved. Individual exposures were dependent upon the ambient temperature, ranging from 20–60s in $K_s$ and 90–120s in $J$. The typical background sky level in $K_s$ was 20,000-25,000 counts, with a maximum allowed level of ~30,000 counts. Detector nonlinearity can be corrected to better than 1% up to 45,000 counts; the maximum allowed level is designed to ensure that 2MASS stars with $K_s > 12.5$, which are used for photometric calibration, have peak fluxes below this level.

2.4. Observing Conditions

Data were obtained on the KPNO 2.1m during an allocation of 97 nights spanning 2001 December to 2004 December. While photometric conditions were not required, usable data were obtained on only ~50% of these nights due to a combination of suboptimal weather conditions and telescope mechanical failures. Observations were coordinated with the NOAO Survey Program "Toward a Complete Near-Infrared Spectroscopic and Imaging Survey of Giant Molecular Clouds" (PI: Lada). The two surveys shared nights to maximize observing efficiency since the target fields for the two groups lie at complementary right ascensions.

3. REDUCTIONS

Survey imaging was reduced using the LONGLEGS pipeline (Roman et al., in prep., and Gonzalez et al., in prep.), which employs standard infrared reduction procedures. Lin-
is the photometric zeropoint, FWHM is the full width half-maximum of the point spread function (PSF) at the field center, and $\sigma$ is the rms noise in each image.

$w = \frac{10^{m_0}}{\sigma(FWHM)^2}$

where $m_0$ is the photometric zeropoint, FWHM is the full width half-maximum of the point spread function (PSF) at the field center, and $\sigma$ is the rms noise in each image.

4. CATALOG PROPERTIES

We construct $K_s$-selected catalogs for each survey subfield using Source Extractor version 2.3 (SExtractor, Bertin & Arnouts 1996), using dual image mode to measure the $J$-band photometry within the same regions. Detection is performed in $K_s$ with a 0.76" FWHM gaussian convolution kernel, and we impose a 5\(\sigma\) object detection threshold. Weight maps are also used to minimize detection of spurious objects.

The catalogs for the individual subfields are then merged, with strict right ascension and declination boundaries defined between subfields to avoid double-counting of objects. We use completeness simulations, described below, to compute more realistic estimates of the magnitude errors than those provided by SExtractor, since the simulations can correctly account for correlated noise across pixels and the impact of background fluctuations. The typical magnitude errors from the simulations are roughly 2-3 times as large as the SExtractor errors for most apertures, and larger for the 20" aperture and the SExtractor automatic aperture (“AUTO”), which is designed to give an estimate of the total magnitude.

4.1. Survey Depth

The depth of the survey is position-dependent due to both instrumental aberration and shorter effective exposure times near the stack edges. The most appropriate way to quantify this variation is via completeness simulations for mock catalogs. We perform such simulations for each field to generate 50% completeness maps. Schematically, the design of the simulations is as follows.

First, we require a two-dimensional model for the point spread function for each field. For this we take an empirical approach – we use data from the dense stellar fields observed by the star formation survey (see §2.3) during the same observing run. We select the individual frames with the best seeing, and from these data generate a lookup table of the coordinates of bright, unsaturated stars. Several of the runs lack imaging from the star formation survey; for these we boot-
strap off the survey data, using stars from the survey fields with the best seeing. To test the reliability of this bootstrap approach, we also run bootstrapped simulations for several fields with stellar template data. In these instances the completeness limits agree to $\lesssim 0.05$ mag in the field center and $\lesssim 0.1 \pm 0.15$ mag in the corners.

Second, we randomly select a location in the final image to insert a fake galaxy, and compute the corresponding location in each individual frame. We then generate a fake galaxy, convolve it with the nearest PSF star for each individual frame, combine these convolved model images, and add the galaxy into the final image.

For every field, in both the $J$ and $K_s$ filters, we insert 5000 fake galaxies with magnitudes spanning the completeness limit. The effective radii of these galaxies are chosen to uniformly span the range of values seen at $z = 1$ from 

\begin{equation}
\text{Ferguson et al. (2004), who measured the distribution of half-light radii of distant galaxies in the Hubble Deep Field–North and Chandra Deep Field–South.}
\end{equation}

Because the primary science goals of the survey focus upon the elliptical galaxy population at $z > 1$, we do not attempt to reproduce the full morphological distribution seen at this epoch. Instead, all mock galaxies used to calculate the completeness limits are pure bulges, with a distribution of effective radii in the range $0.07 \ldots 0.5''$ ($0.5\text{--}4$ kpc at $z = 1$). While obviously a simplification, in practice the bulk of the objects detected in the survey are unresolved in the \textsc{FLAMEX} imaging data, making this a reasonable approximation even for disk galaxies. To verify this assertion, we reran the simulations in two subfields using only spiral galaxies with scale lengths $r_d = 0.6''$ ($4.8$ kpc at $z = 1$). The derived completeness limits were consistent to within 0.1 magnitudes with the results for pure bulges.

We use the output of the simulations to derive two-dimensional maps of the 50% completeness limit for aperture and AUTO magnitudes measured with \textsc{SExtractor}. Figure 4 shows the derived map for a representative subfield. As expected, the off-axis aberrations degrade the survey depth in the corner regions. Statistical uncertainties for these maps can be derived via bootstrap resampling: in the image centers the completeness values have uncertainties of $< 0.03$ mag, while in the corners the uncertainties are $\sim 0.1$ mag. These values are slightly smaller that the systematic uncertainties evidenced by comparison of simulations using the bootstrap stellar templates with those from the star formation fields (see above).

In Figure 5 we plot the survey area as a function of the 50% completeness depth in the Boötes region for 6'' diameter aperture magnitudes, incorporating the exposure maps to reproduce the effect of masking and dithering. More than 90% of the survey region is complete to $K_s = 19.2$, with 50% being complete to $K_s = 19.5$.

### 4.2. Star-Galaxy Separation in Color Space

\textsc{FLAMEX} is the first deep, wide-area near-infrared survey conducted in two filters. Our primary motivation for obtaining both $J$ and $K_s$ data was to efficiently isolate the $z > 1$ population, and these two bands, when combined with the optical \textsc{NDWFS} data (and/or with \textsc{IRAC} data), are particularly valuable for deriving robust photometric redshifts at $z \gtrsim 1$ (Brown et al., in prep.; Brown et al., in prep.). The combination of near-infrared (NIR) and optical photometry from \textsc{FLAMEX} and the \textsc{NDWFS} also find a number of other uses, including star-galaxy separation.

The variable PSF noted above precluded use of structural information to separate the star and galaxy populations in the \textsc{FLAMEX} data, but color information is an effective substitute. The $J - K_s$ color alone provides a simple means of performing star-galaxy separation, as can be seen in the color-magnitude diagram (Figure 9). Galactic stars with types earlier than K5 lie at $J - K_s = 0.8$; later types have bluer colors, with types later than M5 occupying a locus at $J - K_s = 0.4$ (Finlator et al. 2000). Galaxies, which occupy the redder lo-
stellar counts at $K_s \approx 19$ indicates that we may be misclassifying up to 5% of the galaxy population as stars if this is not an intrinsic feature of the stellar number counts. This systematic should be considered for any work involving either high-precision modelling of the number counts or statistical analysis of the local faint galaxy population.

Figure 8 also provides a comparison of the FLAMEX number counts with results from the 0.2 deg$^2$ Calar Alto Deep Imaging Survey (CADIS, Huang et al. 2001), one of the largest previous $K_s$ surveys to comparable depth. Once a completeness correction is applied to the galaxy counts (dotted-dashed curve), the faint-end FLAMEX number counts are consistent with CADIS to $K_s \gtrsim 19.5$. This agreement at the faint end provides validation for the completeness simulations described in §4.1.

Near-infrared galaxy number counts are also a classic diagnostic for constraining models of galaxy evolution (for example, Moustakas et al. 1997; Huang et al. 2001; Chen et al. 2002; Cristóbal-Hornillos et al. 2003). At these wavelengths the K-corrections are small, and the luminosities are both less affected by dust and less sensitive to recent star formation than optical number counts. These factors result in samples that are closer to mass-selected and hence simpler to model. While the magnitude regime probed by the FLAMEX data is not new, the large area afforded by this survey provides significantly greater statistical precision than previous work, enabling refined modelling. Realistic semianalytic models, which attempt to simultaneously match the observed counts in $K_s$ and other passbands (such as Nagashima et al. 2002), are the optimal means for using this information. Such a detailed analysis is beyond the scope of this paper; however, in Figure 8 we compare with a simple classical model to illustrate both the utility of this data set and its precision relative to previous studies.

We use extendable galaxy number count model, $n_{\text{cmd}}$, from Gardner (1998) with the same spectral templates and morphological mix of ellipticals and spirals as Gardner (1998). Similar to Cristóbal-Hornillos et al. (2003), we take the formation redshifts to be $z = 2$ for ellipticals and $z = 1$ for spirals, and add a component of star-forming dwarf galaxies with faint end slope $\alpha = -1.5$. For the general galaxy population we use the Schechter function parameters from Kochanek et al. (2001), while for the star-forming dwarf population we use the same prescription as Gardner (1998) and Cristóbal-Hornillos et al. (2003), but with $\phi_0 = 3.5 \times 10^{-3} h_{50}^3$ Mpc$^{-3}$ (roughly a factor of two lower than these studies). As found by Cristóbal-Hornillos et al. (2003), this type of model qualitatively fits the number counts over much of the observed magnitude range, albeit with some residual deviation. Most notably, FLAMEX and the other surveys yield fewer counts than the model at the brightest magnitudes. The FLAMEX number counts also exhibit an excess at the faint end ($K_s \gtrsim 19$) that is statistically significant with regard to the plotted Poisson uncertainties, albeit at a level that is small compared to the statistical uncertainties for most of the other samples shown. While an excess is also evident in the faintest CADIS data point, we caution against overinterpretation of this feature because this upturn occurs in the regime where our completeness correction is significant.

4. DISCUSSION

The fundamental motivation for the FLAMINGOS extragalactic survey is to facilitate systematic study of the evolution of massive galaxies and galaxy clusters at $z = 1 - 2$.

4.3. Number Counts

Galaxy number counts provide a useful means of testing the reliability of both the star-galaxy separation (§4.2) and the completeness simulations (§4.1). In Figure 8 we show the differential number counts for all sources in Boötes. Using the star-galaxy color separation, we split the number counts into the star and galaxy contributions. The slight upturn in the

cus of objects, are well-separated from the stars for $z \gtrsim 0.05$.

While the $J - K_s$ color alone provides a reasonable means of performing star-galaxy separation, inclusion of the NDWFS optical photometry can be used to improve the separation. We have generated a matched catalog combining the NDWFS third data release (DR3: Iannuzzi et al., in prep) and FLAMEX data. Detections in the different bands were matched if the centroids were within 1" of each other. For extended objects, detections in the different bands were matched if the centroid in one band was within an ellipse defined using the second order moments of the light distribution of the object in another band. The stellar sequence can be seen to cleanly separate from the galaxy locus, with the M stars being relatively redder in $B_V - I$ than the bluest galaxies, and the G stars remaining bluer in $J - K_s$. There remains a modest overlap between faint, nearby galaxies and the G star population, but the cut shown in Figure 7 overall provides an efficient means of separation with $\lesssim 5\%$ misidentification of galaxies at faint magnitudes ($K_s \approx 20$).

13 This ellipse was defined with the SExtractor parameters $2 \times A_{\text{WORLD}}, 2 \times B_{\text{WORLD}},$ and $\text{THETA}_{\text{WORLD}}$. 
5.1. EROs

First discovered by Elston et al. (1988), extremely red objects (EROs) are traditionally defined as objects with $R - K_s > 5$ (although a range of definitions exist in the literature; see McCarthy 2004). While initially speculated to correspond to a population of protogalaxies at $z > 6$, the ERO population is now understood to be predominantly comprised of two distinct types of galaxies – dusty starbursts and galaxies dominated by old stellar populations, both at $z \sim 0.8 - 2$ (e.g., Elston et al. 1989; Cimatti et al. 2002; Yan et al. 2004). For the dusty starbursts, strong extinction in the rest-frame near-ultraviolet drives the observed color; for the old galaxies, the red color is a simple consequence of the 4000 Å break passing redward of $R$-band. These two populations together are believed to constitute the dominant progenitor population for present-day elliptical galaxies, a belief that is supported by their space densities (Daddi et al. 2000) and strong spatial clustering (Daddi et al. 2000; Brown et al. 2005) but see Yan et al. (2004) for concerns with this interpretation. However, as a consequence of the strong spatial clustering and relatively low surface density of EROs, large area surveys are required for precise statistical analysis of the population.

The FLAMEX survey provides an order of magnitude increase in EROs sample size compared to other recent studies. We define EROs as being objects with $R - K_s > 5$ within a 6′ aperture, imposing the additional requirement that $J - K_s > 1.2$ to eliminate potential contamination from stellar sources with spurious optical photometry (Figure 19). By this definition, in the Boötes field alone we have over 7,000 EROS at $K_s < 19.5$ (Figure 19); for comparison, the largest sample used thus far to study the clustering of EROS contained 671 objects down to $K_s = 18.4$ within a 1.4 deg$^2$ region in the NDWFS Boötes field (Brown et al. 2005). The FLAMEX counts are consistent with previous work, with the advantage that the large field enables identification of the brightest, rarest EROS and measurement of the number counts as bright at $K_s \approx 17$. This sample is also sufficiently large to begin to quantify the number density distribution as a joint function of magnitude.
We apply no completeness correction to the FLAMEX data, and hence the true surface density exceeds the FLAMEX points for and $R$. Shifts. The original plan for this program was to use the joint shifts, and then detect galaxy overdensities within redshift FLAMEX and NDWFS data sets to derive photometric redshifts, provides an efficient means of detecting clusters at this morphological evolution of cluster galaxies.

Galaxy Clusters

One of the principal motivations for FLAMEX is identification of a large sample of galaxy clusters at $z > 1$. In the standard paradigm of hierarchical structure formation, we expect the formation of the first massive galaxy clusters to occur at $z = 1 - 2$. The comoving cluster number density at $M > 10^{14} M_\odot$ increases by roughly a factor of 30 between $z = 2$ and $z = 1$ (WMAP cosmology), with the precise number density and degree of evolution strongly sensitive to the details of the underlying cosmological model (particularly $\sigma_8$ and $\Omega_M$). Aside from the cosmological applications (see for example [Haiman et al. 2001, Borgani et al. 2001, Wang et al. 2004]), detailed studies of homogeneous cluster samples at this epoch are essential for understanding the evolution of the cluster galaxy population and how the interplay between the galaxies and host clusters impacts this evolution. Observations at this epoch constrain the evolution of the halo occupation distribution (HOD), the formation epoch of cluster ellipticals, evolution of the color-magnitude relation, and the morphological evolution of cluster galaxies.

Infrared imaging, coupled with shorter wavelength photometry, provides an efficient means of detecting clusters at this epoch. The infrared data enable construction of roughly stellar mass-selected galaxy samples, and the combination of optical and infrared data enables derivation of photometric redshifts. The original plan for this program was to use the joint FLAMEX and NDWFS data sets to derive photometric redshifts, and then detect galaxy overdensities within redshift slices. We developed a detection technique within this framework that is generically applicable to any photometric redshift catalog. The photometric redshift catalog is used to subdivide the data set into overlapping redshift bins, and we then employ a wavelet algorithm with bootstrap resampling to identify statistically significant overdensities on a fixed physical scale (a complete description will be provided in Gonzalez et al., in prep.).

Over the course of the survey this original plan has evolved in one significant regard. Joining forces with the IRAC Shallow Survey (Eisenhardt et al. 2004), we are now using the combination of NDWFS, FLAMEX, and IRAC (3.6$\mu$m and 4.5$\mu$m) photometry to derive more robust photometric redshifts (Brodwin et al., in prep.), and probe more deeply than would be possible with either the NDWFS and FLAMEX or NDWFS and IRAC data sets alone. The IRAC data are deeper than FLAMEX, allowing us to push further down the cluster luminosity function, while the FLAMEX data significantly reduce the scatter in photometric redshifts at $z \gtrsim 1.4$ (Brodwin et al., in prep.). We also now fold in the full redshift probability distribution for each source, which minimizes the noise from galaxies with poorly constrained redshifts. Additionally, our joint team is using the same technique in a complementary survey to detect clusters within the full 9.3 deg$^2$ NDWFS Boötes field using only the NDWFS and IRAC data (Eisenhardt et al., in prep.).

In this paper we present one of the first spectroscopically confirmed $z > 1$ clusters detected with the combined NDWFS, FLAMEX, and IRAC data sets, CL1432.5+3332.8 at $z = 1.11$ (Figure 11). To identify clusters within the FLAMEX region we perform a wavelet search using the photometric redshift probability distributions derived from the combined data sets,
Fig. 11.— The four image panels, each $3' \times 3'$, show the core region of CL1432.5+3332.8 in $B_W$, $I$, $K_s$, and IRAC 4.5$\mu$m bands. The cluster is visible as an excess of red galaxies in the $K_s$ and 4.5$\mu$m bands, and in the $K_s$–band image we overlay circles to denote all galaxies with photometric redshifts $1 \leq z \leq 1.2$. The centroid of the cluster detection is located at $\alpha = 14h32m29.2s$, $\delta = +33d32m48s$ (J2000), which is near the dense clump of red galaxies in the upper, central part of the images.

Fig. 12.— Spectrum of a galaxy at $z = 1.110$ in CL1432.5+3332.8, after smoothing with a 5 pixel boxcar filter. Several absorption features common to early-type galaxies are marked.

with the wavelet scale size defined to detect structures with physical scales $r \approx 200–800$ kpc. Monte Carlo simulations are then used to quantify the significance of each detection. This search identifies the cluster CL1432.5+3332.8 as one of the three highest significance overdensities at $z > 1$, with an estimated redshift $z = 1.2$ (Figure 11).

Spectroscopic confirmation of this candidate was obtained on 3 June 2005 UT using LRIS on Keck 1. We used a single slit mask for the observations which were carried out in clear conditions with 0.9 arcsec seeing. Five 1800s exposures were obtained, with the target galaxies shifted within the slitlets between each exposure. The data were reduced using standard long slit techniques (e.g. Stanford et al. 1997). The resulting redshifts include 8 galaxies at $1.10 < z < 1.12$. Of these, five exhibit absorption line features indicative of old stellar populations (Figure 12), arguing that we are observing a cluster with an established early-type population. A histogram of the redshifts is shown in Figure 13. The resulting velocity dispersion is $\sigma = 920 \pm 230$ km s$^{-1}$, as calculated using the gapper method (Beers, Flynn, & Gebhardt 1990), confirming that CL1432.5+3332.8 is a massive galaxy cluster.

The cluster CL1432.5+3332.8 is presented here as a proof
of concept to demonstrate that we can successfully identify clusters at $z > 1$ using the combined Boötes data sets. A single cluster detection of course cannot constrain the fidelity or completeness of catalogs derived with this data set. These are issues that will be addressed in subsequent papers, and in particular we refer the reader to Stanford et al. (in prep.) and Eisenhardt et al. (in prep.) for further explorations of the photometric redshifts and cluster catalogs derived from the NDWFS+FLAMEX+IRAC and NDWFS+IRAC data sets.

5.3. Public Catalogs

The FLAMINGOS Extragalactic Survey received time through the NOAO Large Survey Program and provides public access to the catalogs for the full FLAMEX region. The most recent version of the catalogs, accompanied by a detailed description, is posted on the web (starting September 30, 2005) at the following mirrors: [http://flamingos.astro.ufl.edu/extragalactic/](http://flamingos.astro.ufl.edu/extragalactic/) and [http://www.noao.edu/noao/noadepth/](http://www.noao.edu/noao/noadepth/)

6. SUMMARY

We present an overview of the FLAMINGOS Extragalactic Survey (FLAMEX), a near-infrared imaging survey conducted at the KPNO 2.1m with the FLAMINGOS instrument. FLAMEX is the first deep, wide-area NIR survey to image in both the $J$ and $K_s$ filters, and is larger than any previous surveys to comparable depth. Located within the NOAO Deep-Wide Field Survey regions, FLAMEX is designed to complement the NDWFS optical photometry and other existing multiwavelength public data sets, with the intent that it be a resource to the astronomical community. We therefore make the full catalogs from this program publicly available via the web pages listed in §5.3.

The survey area ($7.1 \text{ deg}^2$) is divided between the northern (Boötes) and southern (Cetus) NDWFS regions, with $4.7 \text{ deg}^2$ in Boötes and $2.4 \text{ deg}^2$ in Cetus. We provide an initial characterization of the data set based upon the $\sim 150,000$ sources detected ($5\sigma$) within the Boötes field. The data in this region reach a median depth of $K_s \sim 19.3$ ($6''$ aperture), with a positionally dependent limiting magnitude that we model using extensive Monte Carlo simulations. Using the Boötes catalog in conjunction with optical NDWFS photometry we are able to perform a color-based star-galaxy separation that is robust for all sources except faint, blue galaxies at $z \sim 0$. We demonstrate that the Boötes number counts are fully consistent with results from previous, smaller area surveys down to $K = 19.6$, but with vastly reduced statistical uncertainty. We discuss the utility of this data set for quantifying the number density and clustering properties of the ERO population. The FLAMEX Boötes catalog alone contains an order of magnitude more EROs than any published studies. Finally, we describe one of the first spectroscopically confirmed clusters at $z > 1.1$, which was identified using photometric redshifts derived from the joint FLAMEX, NDWFS, and IRAC Shallow Survey catalogs.

The authors are deeply grateful to Elizabeth Lada for her many contributions to FLAMINGOS and our survey. In particular we thank her for critical assistance, advice, and guidance during the transfer of the survey leadership. Her personal and professional support were key to the success of the program. We also express our sincere thanks to the NOAO Survey TACs and NOAO for granting time for this survey through the NOAO Survey Program, and to Ron Probst and the observatory staff at Kitt Peak for support of the FLAMINGOS instrument. Additionally, we appreciate the efforts of the full FLAMINGOS instrument team at the University of Florida, including Jeff Julian, Kevin Hanna, and David Hon, and are grateful to Jonathan Gardner for his suggestions as referee. RJE acknowledges support from the National Science Foundation via a PECASE grant (AST-9875448). AHG acknowledges support from the NSF Astronomy and Astrophysics Postdoctoral Fellowship program under award AST-0407085 and from an NSF Small Grant for Exploratory Research under award AST-0436681. The work of MB, PRME, and DS was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with NASA. JJJM acknowledges support from the NASA Long Term Astrophysics award NAG 5-11415. This publication makes use of data products from the Two Micron All Sky Survey, which is a joint project of the University of Massachusetts and the Infrared Processing and Analysis Center/California Institute of Technology, funded by the National Aeronautics and Space Administration and the National Science Foundation. This work is based in part on observations made with the Spitzer Space Telescope, which is operated by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with NASA.

Facilities: KPNO 2.1m (FLAMINGOS), Keck 1 (LRIS), Spitzer (IRAC), KPNO 4m (MOSAIC-1)

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Fig. 13.— Redshift distribution from Keck observations of CL1432.5+3332.8. The solid histogram includes only galaxies with photometric redshifts $0.95 < z \leq 1.25$, while the open histogram includes all spectroscopic sources. The derived redshift and dispersion are $z = 1.109$ and $\sigma = 920 \pm 230 \text{ km s}^{-1}$. 13. Redshift distribution from Keck observations of CL1432.5+3332.8. The solid histogram includes only galaxies with photometric redshifts $0.95 < z \leq 1.25$, while the open histogram includes all spectroscopic sources. The derived redshift and dispersion are $z = 1.109$ and $\sigma = 920 \pm 230 \text{ km s}^{-1}$. The survey area ($7.1 \text{ deg}^2$) is divided between the northern (Boötes) and southern (Cetus) NDWFS regions, with $4.7 \text{ deg}^2$ in Boötes and $2.4 \text{ deg}^2$ in Cetus. We provide an initial characterization of the data set based upon the $\sim 150,000$ sources detected ($5\sigma$) within the Boötes field. The data in this region reach a median depth of $K_s \sim 19.3$ ($6''$ aperture), with a positionally dependent limiting magnitude that we model using extensive Monte Carlo simulations. Using the Boötes catalog in conjunction with optical NDWFS photometry we are able to perform a color-based star-galaxy separation that is robust for all sources except faint, blue galaxies at $z \sim 0$. We demonstrate that the Boötes number counts are fully consistent with results from previous, smaller area surveys down to $K = 19.6$, but with vastly reduced statistical uncertainty. We discuss the utility of this data set for quantifying the number density and clustering properties of the ERO population. The FLAMEX Boötes catalog alone contains an order of magnitude more EROs than any published studies. Finally, we describe one of the first spectroscopically confirmed clusters at $z > 1.1$, which was identified using photometric redshifts derived from the joint FLAMEX, NDWFS, and IRAC Shallow Survey catalogs.
