Subaru Deep Survey I. Near-Infrared Observations

Toshinori MAIHARA
Department of Astronomy, Kyoto University, Kitashirakawa, Kyoto 606-8502
E-mail(TM): maihara@kusastro.kyoto-u.ac.jp
Fumihide IWAMURO, Hirohisa TANABE, Tomoyuki TAGUCHI, Ryuji HATA,
Department of Physics, Kyoto University, Kyoto 605-6802
Shin OYA,
Communications Research Laboratory, Koganei, Tokyo 184-8975
Nobunari KASHIKAWA, Masanori IYE, Satoshi MIYAZAKI, Hiroshi KAROJI,
Michitoshi YOSHIDA
Optical and Infrared Astr. Div., National Astronomical Observatory, Mitaka, Tokyo 181-8588
Tomonori TOTANI
Theoretical Astrophysics Div., National Astronomical Observatory, Mitaka, Tokyo 181-8588
Yuzuru YOSHII
Institute of Astronomy, School of Science, University of Tokyo, Mitaka, Tokyo 113-0033
Sadanori OKAMURA, Kazuhiro SHIMASAKU, Yoshihiko SAITO
Department of Astronomy, University of Tokyo, Hongo, Tokyo 113-0033
Hiroyasu ANDO, Miwa GOTO, Masahiko HAYASHI, Norio KAIUF, Naoto KOBAYASHI,
George KOSUGI, Kentaro MOTOHARA, Tetsuo NISHIMURA, Jun’ichi NOUMARU,
Ryusuke OGASAWARA, Toshiyuki SASAKI, Kazuhiro SEKIUCHI, Tadafumi TAKATA,
Hiroshi TERADA, Takuya YAMASHITA, Tomonori USUDA
Subaru Telescope, National Astron. Observatory, 650 N. Aohoku Place, Hilo, HI 96720, USA
and
Alan T. TOKUNAGA
Institute for Astronomy, University of Hawaii, 2680 Woodlawn Dr., Honolulu, HI 96822, USA
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Abstract

Deep near-infrared images of a blank 2′ × 2′ section of sky near the Galactic north pole taken by Subaru Telescope are presented. The total integration times of the J and K′ bands are 12.1 hours and 9.7 hours, resulting in 5-sigma limiting magnitudes of 25.1 and 23.5 mag, respectively. The numbers of sources within these limiting magnitudes found with an automated detection procedure are 385 in the J band and 350 in K′. Based on photometric measurements of these sources, we present number count vs. magnitude relations, color vs. magnitude diagrams, size vs. color relationships, etc. The slope of the galaxy number count plotted against the AB magnitude scale is about 0.23 in the 22 to 26 AB magnitude range of both bands. The spatial number density of galaxies as well as the slopes in the faint-end region given by the Subaru Deep Field (SDF) survey is consistent with those given by HST-NICMOS surveys as expressed on the AB magnitude diagram. Several sources having very large J − K′ color are found including a few K′ objects without detection at J. In addition, a number of faint Galactic stars are also detected, most of which are assigned to M-subdwarfs, together with a few brown dwarf candidates.

Key words: cosmology: observations — cosmology: early universe — infrared: galaxies — infrared: stars — galaxies: evolution — stars: low-mass — stars: brown dwarfs

1. Introduction

Extremely deep imaging of blank fields is a vital method of delineating the nature of the early universe and gaining general knowledge about the physical conditions at such an early epoch. In this context, the purpose of deep surveys are not only to search for bright, peculiar objects at very high redshift, but to also learn about the overall nature of the early universe. The optical Hubble Deep Field (HDF) images taken by Hubble Space Telescope have presented views different from the present day universe. They showed that faint, irregular, and smaller galaxy populations seem to be much more
abundant, perhaps inherent to the early universe. However, since the faint, high-redshift objects seen in the optical HDF images are deemed to represent rest frame UV emissions, the information is predominantly related to UV-luminous sites, presumably associated with current star formation, rather than the fundamental structure of stellar components in galaxies. On the other hand, a near-infrared deep survey is expected to convey information about the basic galactic structure, or in other words, information related to the fundamental mass distribution. Near-infrared observations may also be crucial to probe galaxies in the most distant region, because the effect of intergalactic reddening, if it occurs, gets smaller at longer wavelengths.

There are already a number of near-infrared surveys (Gardner et al. 1993, Bershady et al. 1998, Yan et al. 1998, Thompson et al. 1999), with spatial coverage, wavelength bands, and limiting magnitudes differing from survey to survey. The observed wavelengths in the near-infrared may correspond to rest frame wavelengths within a much broader spectral span, if objects with redshifts of 5 or even larger are included. As for the deepest near-infrared survey, NICMOS images of a part of the HDF region have provided deep source counts in both the $J$ and $H$ bands (Thompson et al. 1999). The claimed limiting magnitudes are between 27.5 to 28 AB magnitudes at the 80% completeness level. It is interesting to note that the source count vs. magnitude diagrams of both these bands show an appreciably lower number density of galaxies than previous ground-based results. Since the sensitivity of the NICMOS imager in the $K$ or $K'$ band is limited by the thermal radiation of the telescope, extremely deep surveys using ground-based telescopes are important especially in the $K'$ band. Here we present the $K'$ band image as well as that at $J$, both currently the deepest images taken by a ground-based telescope.

In this report, we concentrate on the details of observations using the newly commissioned 8.2 m Subaru Telescope atop Mauna Kea and on data analysis, and then present number count diagrams of galaxies in two near-infrared bands, $J$ (1.25 $\mu$m) and $K'$ (2.13 $\mu$m). We also show the detection and identification of stellar components found in the SDF survey region. Cosmological constants are assumed to be $H_0 = 65$ km s$^{-1}$ Mpc$^{-1}$ and $q_0 = 0.1$ throughout this paper.

2. Observations

2.1. Near-Infrared Camera: CISCO

A near-infrared imaging and spectroscopic instrument called CISCO (Cooled Infrared Spectrograph/Camera for OHS) was used from early April to mid-June 1999 at the Cassegrain focus of the Subaru Telescope. The detailed description of CISCO has been reported by Motohara et al. (1998). Major specifications are listed in table 1.

The filters used in the present deep survey are $J$ (1.16–1.32 $\mu$m) and $K'$ (1.96–2.30 $\mu$m) bands. A fixed exposure time was employed throughout observations, namely, 40 sec in the $J$ band and 20 sec in the $K'$. The exposure times are shorter than the saturation level (about 30%) of the detector readout system, but we adopt them throughout the present survey to secure uniformity in the dithered multiple exposure strategy we adopted (see the following subsection).

2.2. Field Selection

Several years ago we chose two regions suitable for a very deep survey, one each in the northern and southern hemispheres, and we designated them as the Subaru Deep Field (SDF). The selected area in the present near-infrared survey is one of the pre-determined blank sky regions near the north Galactic pole (NGP), as shown in figure 1. The center coordinates of the observed area of SDF-NGP are, RA(2000)=13$^h$24$^m$21.38 and DEC(2000)=+27$^\circ$29$^\prime$23$^\prime\prime$.0. In selecting the SDF survey region, we placed a requirement that a reasonably bright star be located close to the area to serve as a reference star for possible adaptive optics-based observations in the near future. The principles and criteria for selecting the SDF regions are described below:

i) We chose an independent deep survey region because the nature (appearance) of the Universe may have different characteristics from one direction to another. ii) The spatial resolution achieved by the Subaru-CISCO combination has proved to be nearly 0$''$3 or even better under the best conditions, and about 0$''$45 on average, which potentially offers an excellent opportunity to probe remote faint galaxies in the high-redshift Universe. We therefore hope to obtain the deepest survey data in the near-infrared, especially in the 2 $\mu$m region by taking long enough observations. iii) The HDF is at higher airmass at Mauna Kea than that of the SDF. This factor is significant in the latter half of nights from April to June, when the present survey was performed. Note that, although the limiting magnitude of HST-NICMOS is extremely high compared with any ground-based near-infrared imaging, the sensitivity in the $K$ or $K'$ band is higher in the ground-based ones due to larger telescope aperture. The sensitivity of optical bands by Subaru Telescope in terms of total magnitude is expected to be nearly comparable or even higher ($R$-band, for example), despite lower spatial resolution. iv) We should have a reference star nearby for AO-based observations. With the AO system, the spatial resolution is much higher than that of HST-NICMOS in the $H$ and $K$ bands, and the sensitivity is comparable if the exposure time is the same.
v) In selecting SDF, we posed additional requirements, namely, low Galactic HI column density, no nearby bright stars and galaxy (except for the reference star for AO), and no known nearby cluster of galaxies.

2.3. Method of Dithering Observations

We employed the 8-position dithering method in both bands. In the $K'$-band case, 12 consecutive frames were taken at each position before offsetting the telescope towards the next position. The order of 8 positions was chosen so as to make a diamond pattern with a diameter of $8''-12''$. Thus we took 96 frames of 20 sec exposures in a single set of dithering observations, resulting in a total on-source integration time of 1920 sec. The entire process of taking 96 exposures is organized by an "abstract command" (kind of a macro command) issued by the observer workstation which dispatches individual commands to the telescope control system, such as the auto-guiding system, the infrared camera controller, and the telescope itself. Normally, we made observations in one of the two photometric bands, $J$ or $K'$, in one night throughout the SDF project.

When the seeing conditions were fairly good, we preferentially implemented $J$-band observations in the fashion described above. The same integration time of 1920 sec in a set of dithering observations was secured, but by adopting single exposure time of 40 sec with 6 consecutive exposures at one position instead of 12 in the $K'$ band case, in view of the lower sky background level of the $J$ band. The positional accuracy of each offset movement relative to the origin of coordinates, when the direction is put back, has proved to be on the order of $0''.05$ under normal conditions, but sometime it is as large as $0''.2$, as measured by the center-of-gravity fluctuation of a bright object on the recorded frames. We determined offset values of each frame by the measured coordinates of a particular star in the frames, not by referencing the recorded FITS data.

2.4. Log of Observations

Observations of the SDF survey started on April 3 and ended on June 22, 1999, using available nights for CISCO observations during the telescope commissioning phase. Since the SDF survey was supported by the Subaru Project Office as a priority project during this period, we devoted almost all nights with observing conditions described above. The SDF survey was supported by the Subaru Project Office as a priority project during this period, and ended on June 22, 1999, using available nights for CISCO observations during the telescope commissioning phase.

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During this period, the best seeing data were recorded on May 26; a couple of frames of a field star with 20 sec exposures had PSFs of $0.20''$ at FWHM. Although the individual frames have different image resolutions, mostly attributed to the day-to-day variations in seeing conditions, we just accumulated all the acquired frames without considering the difference in seeing in the present analyses. Thus the present near-infrared SDF survey has ended up with the target dedicated time of 12.1 hours in the $J$ band and 9.7 hours in the $K'$ band.

3. Data Reduction and Source Detection

Using all the frames taken in a set of automatic dithering observations, we first created a sky frame out of 96 dithered exposures by the standard median sky method. In this procedure, each frame is first divided by the flat frame and is also corrected by a bias frame. The flat frame is produced from a large number of sky frames by a method similar to the co-adding method used for creating the standard median sky but using all the frames obtained in the long-term SDF observations. In generating the sky frame, the contribution of individual stars was maximally reduced by masking all the discernible stars. Then, we co-added all the sky-subtracted frames in which the offsets of the shift-and-add procedure had been determined at a sub-pixel level from the bright sources in each frame. The pixel values with scatters exceeding $3\sigma$ were rejected, and therefore possible cosmic ray events or rare pixel events due to unstable behavior were excluded.

The reduced $J$ and $K'$ band images are shown in figures 2 and 3, respectively, and the color composite created from these two bands is presented in figure 4. Throughout these images, the center position is $13^{h}24^{m}21.38$ in RA, and $+27^{\circ}29^{\prime}28.3$ in Dec at the epoch of 2000.0 as determined by the astrometric measurement based on the position of a bright reference star located in the northeastern corner of the SDF field, which is just trimmed out in these figures. The unvignetted area presented in figure 2 is $118'' \times 114''$ with a pixel scale of $0''.116$ per pixel. The stellar image sizes of figures 2 and 3 are $0''.45$ in FWHM for the $J$ band, and $0''.35$ for the $K'$ band. In producing the combined color image of figure 4, we applied a smoothing filter to the $K'$ image to match the image size in $J$ of $0''.45$ at FWHM.

For source detection and photometry on the reduced SDF frames, we employed the routine called SExtractor developed by Bertin and Arnouts (1996). Before applying it, images of both bands were smoothed out by a Gaussian filter that makes image resolution $0''.55$ at FWHM because we have learned that filtered images give optimal source detection capability with less spurious source detection by iterative trials of SExtractor. We define the detection threshold as the $1.50\sigma$ level of surface brightness fluctuation of the sky, which corresponds to $25.59$ mag arcsec$^{-2}$ in the $J$ band and to $24.10$ mag arcsec$^{-2}$ in the $K'$ band. If an assemblage of at least 18 pixels, which are connected to each other, has an excess signal over the thresholds, we regarded it as positive detection. We have thus defined the isophotal magnitude
by integrating the signal within the region that exceeds the threshold level. In addition, we have listed total magnitude as well as aperture magnitude in our primary catalog.

The total numbers of sources detected and cataloged through the above procedures are 911 and 939 in the $J$ and $K'$ bands, respectively. Note that the catalog may contain spurious sources due to the effect of noise. Regardless of the reliability of each source, we have accomplished photometric calibration of the data by a reference star in the same frame whose brightness has been determined by measuring standard stars: FS23 and FS27, selected from the UKIRT faint star catalog (Casali & Hawarden 1992). The resultant calibrated catalog will be reported elsewhere when optical data are obtained.

To obtain a diagram of number count versus total magnitude, we have to assess the spurious detection of sources due to the effect of statistical noise and also the error of source photometry. For noise evaluation, we first created a reference frame (artificial blank sky) using SDF raw frames, but with all traces of detected objects removed. To ensure removal of much fainter objects from the reference frame, we also referred to the co-added object frames for identification. The final blank sky frames in both bands were thus obtained by co-adding all the frames without adjusting the dithering offset. Then, by applying SExtractor to the sky frame, we evaluated the rate of spurious source detection, and thus obtained the correction factor for the raw result. It was found that spurious source detection tends to affect the source count discussed below, but only in the $S/N < 5$ range.

In the next step, a number of artificial objects (mock galaxies) with a wide range of brightness as well as source size were embedded in the real image frames. The brightness distribution of the objects in the faint region are assumed to be represented by a slope of $\sim 0.23$ (derived from the raw data with $S/N > 5$). In the course of this calculation, the SExtractor software was applied multiple times, to establish a relationship between the input photometric brightnesses and the measured ones. The results of simulations are shown in figure 5, where each dot represents the measured magnitude for an input object of a given magnitude. The relation is expressed by a matrix-type operator. This method has been employed in galaxy count studies (e.g., Smail et al. 1995; Minezaki et al. 1997). Based on the matrix, we can evaluate errors in photometry, and also correct the raw number count data using the completeness curves as shown in the lower panel of figure 5.

The source counts against magnitude, with and without the correction for completeness, are plotted in figures 6 and 7, where data points of total, isophotal, and aperture magnitudes are presented for comparison. As seen from these figures, the correction becomes significant at magnitudes larger than 25.5 mag in $J$ and 24 mag in $K'$. If we define a $S/N$ of 5 for definite detection, the limiting magnitudes are 25.1 mag in $J$ and 23.5 mag in $K'$, with the number of sources being 385 and 350, respectively. The magnitudes corresponding to detection completeness of 50% are 24.4 mag in $K'$ and 25.8 mag in $J$.

4. Results and Discussion

4.1. Corrected Number Counts

Corrected number counts in both the $J$ and $K'$ bands are tabulated in Table 3. In figures 8 and 9, we plot them for $J$ band sources and for $K'$ band sources, respectively. Also plotted are those of other surveys taken from the literature. In the table and figures, our data refer to total magnitude, while some of the other data points are defined by aperture magnitude. Source sizes in the faintest magnitude range are very small, and in general, smaller than the aperture adopted in most of the aperture photometry. This means that the aperture magnitude is virtually the same as total magnitude, since the aperture is normally taken to be larger than the seeing size. In this first report of the SDF survey program, we shall concentrate mostly on the sources having relatively high $S/N$-ratios, $S/N$ of $\sim 5$ or more. We will prepare a separate paper in which galaxy counts, colors, and morphologies at the faint end will be examined.

Here it should be noted that the contribution of stars to the number counts is estimated by a simulation, and that the point sources (14 objects in the SDF field have been identified) have been excluded. The actual procedure of the simulation by which a criterion to identify stellar objects will be described in a later section. Some quasi-stellar objects (QSOs) may also be included in the thus identified stellar objects. However, their contribution to the number count should be smaller than that of stars in view of the result found by Huchra and Burg (1992), who reported that the fraction of all the types of Seyfert galaxies at the absolute magnitude limit of $-20.0$ is about 1.3% in the CfA redshift survey. Brighter objects with a stellar appearance are expected to be less abundant than Seyfert galaxies.

In figure 10, we plot the galaxy number counts against the AB magnitude scale to compare the slope as well as absolute number density of different photometric bands obtained so far. Here the HST-NICMOS $J$- and $H$-band data are taken from Yun et al. (1998) and Thompson et al. (1999). In these figures, published data of galaxy number counts by the authors are also plotted. The spatial number density of galaxies in the SDF appears to be a good match with that given by Yun et al. (1998), who presented the $H$-band number count obtained with HST-NICMOS operating in the so-called parallel mode. It is also consistent with Thompson et al. (1999) at the
faint end (at \( H = 23.5 - 26 \ \text{AB mag} \)) but deviates much at magnitudes brighter than 22.5 mag possibly due to lower statistics. In contrast, the absolute number densities given by some of the past ground-based surveys differ substantially from that of the present SDF survey in the magnitude range \( \geq 23 \ \text{AB mag} \). It would still be necessary to increase survey areas as well as to obtain higher S/N ratios to examine the possible structural inhomogeneity of the Universe. Nevertheless, the SDF area is so far the largest among deep near-infrared surveys, and therefore should be a more accurate representation of the global distribution of galaxies in the Universe. Another important result derived from figures 8, 9, and 10 is that the near-infrared color \( J - K' \) is almost constant at least in the AB mag range from 22 to 25.5 mag, and the median color is \( \sim 1.4 \), as described next.

4.2. Extragalactic Background Light (EBL)

As for the slope of the galaxy count in the \( K' \) band, we have to be careful in interpreting it because we have assumed a slope of 0.23 in the model source number count in the simulation process. This affects the result at the faint end, although the slope is iteratively corrected and has converged at 0.23. It should also be noted that this slope is derived by applying the correction factor of completeness, in which we have assumed, for simplicity, that these faint galaxies are point sources, since apparent sizes of detected faint sources are small enough. Figure 11 shows the contribution to the EBL in the \( K' \) band as a function of apparent magnitude. This figure shows that we have already resolved the EBL consisting of discrete galaxies in this band. The optical galaxy counts in the HDF have also shown such a signature (see Pozzetti et al. 1998). The present result of the SDF in the near-infrared band gives clear evidence that the bulk of EBL is contributed by an integration of fairly bright discrete sources, consistent with a similar diagram shown by Pozzetti et al. (1998), who compiled available \( K' \)-band data.

Now we can evaluate surface brightness as EBL by integrating individual sources in a wide magnitude range of \( 10 \leq K' \leq 25 \). The estimate using our data as published count data is \( \sim 5.1 \times 10^{-20} \ \text{erg cm}^{-2}\text{s}^{-1}\text{Hz}^{-1}\text{sr}^{-1} \) in the \( K' \) band. The major contribution to EBL is made by fairly bright galaxies of about \( K' \sim 15-20 \ \text{mag} \). Note that the contribution of sources fainter than \( K' = 25 \ \text{mag} \) to surface brightness is small, since the slope is no more than 0.23. Extrapolation both into the faint and bright end adds at most \( \sim 5\% \) of the above value of the EBL flux. It should be noted that these estimates are based on the completeness correction that assumes that all galaxies are small in size. Since the completeness correction may be larger than this, if there are galaxies with larger spatial extents, and thus with lower surface brightnesses. Then the above estimate may be an underestimate of the \( K' \)-band EBL. However, as seen in figure 11, the bulk of EBL comes predominantly from relatively bright galaxies at \( K' \sim 15-20 \), so that we consider that the uncertainty in the counts at the faintest magnitudes in the SDF does not significantly change the above estimate of the EBL.

4.3. Near-infrared Color and Morphology of Faint Galaxies

Figure 12 shows the \( J - K' \) color vs. \( K' \) magnitude diagram of near-infrared sources. Here we omitted sources that have been assigned as stellar objects. Since the photometric aperture of total magnitude in the \( J \) band is not always the same as for the \( K' \) band, it is necessary to define a color with the same aperture of the two bands. Therefore we have calculated colors of smaller sources in figure 12 in terms of photometric magnitudes defined by 10 pixels, i.e., a 1″16 diameter. Even if an object is picked up only in the \( J \) band and is not detected by our criteria in the \( K' \) band, a \( K' \) photometric brightness is artificially given by measuring encircled intensity with the same aperture as that defined in the \( J \) band, thus providing the \( J - K' \) color of the sources.

The median color is shown by the filled squares in figure 12, while the thin lines represent color magnitude curves for four categories of galaxy, E/S0, Sbc, Scd, and Irr, all of which being drawn by applying only K-correction (Coleman et al. 1980; Yoshii & Takahara 1988). Pozzetti et al. (1996) presented a study of the pure luminosity evolution (PLE) model to examine faint galaxy count data from the U- to the K-band in which luminosity evolution as well as mild spectral evolution are incorporated, and they have shown that simple PLE models are in general considered as baseline models of faint galaxy counts. However, as they also noted, the discrepancy between PLE models and the \( K' \) band data is more significant than optical bands. One may notice that, as shown in figure 12, the median color of sources is fairly constant up to about \( K' = 22 \ \text{mag} \), and then gets slightly redder as the brightness gets fainter, although the standard deviation is large. As for the color of faint galaxies, Saracco et al. (1999) argued that the median \( J - K' \) color of galaxies gets redder from 1.1 to 1.5 up to \( K' = 19 \ \text{mag} \), and then it tends to be somewhat bluer in the fainter magnitude range. Such a trend is not necessarily inconsistent with figure 12, but it is noteworthy that the color is, by and large, constant at least in the magnitude range where the selection effect is still small (SN>5 for both bands), but with a significant statistics. In order to interpret observed galaxy counts as well as the color magnitude relation, it is necessary to introduce galaxy evolu-
tion models in which different formation epochs \((z_f)\) for different galaxy categories are presumed. Such quantitative analyses for the present \(J - K'\) color vs. luminosity relation will be discussed in our forthcoming paper.

In figure 12, sources with \(J - K'\) colors redder than 2.5 are discerned, where 4 objects out of 9 are not detected in the \(J\) band. These large \(J - K'\) color objects in the faint region at about \(K' = 23\) mag are likely to be remote galaxies as judged from the apparent spatial extent as well as the derived “stellarity” index determined by SExtractor. Some of the reddest objects in the SDF survey images are tabulated in table 3 and also shown in figure 13. The listed objects are relatively bright in \(K'\) (<22.5 mag) and have \(J - K'\) colors equal to or larger than 2.8. The object on the left appears to be a merger system, and the third one from the left may be representing an interacting system, although it is possible that they could just appear as close neighbors.

Extremely red objects with unprecedentedly large \(J - K'\) colors located in the faint magnitude domain are currently given special attention in connection with galaxy formation in the earliest epoch. Dickinson et al. (2000) found an unusual infrared object in the HDF North field detected only in the \(H\) and \(Ks\) bands with no detectable fluxes shorter than the \(J\) band. It has the \(H - K\) color of about 1.2 with the \(J - H\) color limit of nearly 3. They discuss three possible interpretations, which are, i) a dusty \(z > 2\) galaxy, ii) an old elliptical at \(z > 3\), or iii) a \(z > 10\) Lyman break galaxy. Similar objects were reported by Yahata et al. (2000), who list possible extremely high redshift galaxies in the HDF South NICMOS field. Nine objects appear to have a break between 1 to 2 \(\mu m\). Redshifts of the source have been derived from \(U\) - to \(K\)-band data by a method of photometric redshift determination that spans from \(z = 7.66\) to 15.45.

Since we have so far not acquired any data in the optical bands for the extreme SDF objects, we cannot infer photometric redshifts on a firm basis. Nevertheless, infrared color as large as \(J - K' \geq 2.8\) suggests these objects belong to the same population of the HDF-South NICMOS objects having redshift \(z \geq 10\). It is however necessary to get optical band photometric information, as well as spectroscopic data with highly sensitive instruments such as the OHS, for further examination of these objects. We can determine whether they are moderately redshifted \((z \sim 2 - 4)\) ellipticals or unprecedentedly high-redshift galaxies.

### 4.4. Faint Stellar Populations in the Galaxy

In order to extract stars from the table of SDF sources detected at \(S/N > 5\), we have developed a procedure of star-galaxy separation based on a detectivity test using mock stars. It is similar to the completeness test of the source count in conjunction with the SExtractor. The criteria for identifying stars from SDF sources are basically expressed by the following two conditions. The first one is that the FWHMs are smaller than \(0.47\), and \(0.34\) for bright sources, in the \(J\) and \(K'\) bands, respectively. In addition, based on the simulation, it is found that the limiting sizes should be corrected in the fainter source region, by adding terms: i.e., \(10^{(m - m_e)/2.5}\), where \(m\) is the magnitude of the source, and \(m_e = 26\) and 25 mag for the \(J\) and \(K'\) bands, respectively. The second condition is that the stellarity index which is given by SExtractor is larger than 0.8. By adopting these criteria, 14 objects are classified as stars on a fairly firm basis. Naturally, possible stellar objects with stellarity indexes larger than 0.8 could be excluded due to the first criterion. See Nakajima et al. (2000) for the detailed procedure of galaxy-star separation we have developed. The completeness of identification of stars has also been estimated with this simulation, which is about 60% for sources brighter than 24 mag in the \(J\) band, or 23 mag in the \(K'\) band. We plot the SDF objects in the FWHM vs. \(J - K'\) color diagram as shown in figure 14, where objects satisfying the above criterion are marked by open star symbols.

It is interesting to note that several relatively bluer \((J - K' \sim 0.6)\) stellar objects appear to concentrate in the lower left: a well-confined region on the diagram. These are presumably extreme \(M\) subdwarf (ESD) stars as classified by Leggett, Allard & Hauschildt (1998). The extreme \(M\) subdwarfs are supposed to be members of the Galactic halo and have very low metallicity. They are listed in the tables of low mass stars presented by Leggett, Allard, & Hauschildt (1998), and are characterized by effective temperatures of about 3000 K and by masses of 0.09 \(\sim 0.15\) \(M_\odot\). From their photometric data it is seen that the brightness range of ESD stars is from \(K=11\) to 15 mag and that the \(J - K'\) color is 0.65 \(\pm 0.15\). In view of these, some 10 stars in the confined region of figure 14 are most probably extreme \(M\) subdwarfs. Since their absolute magnitudes span from \(M_J=9.5\) to 10, we should have reached about 8 kpc to capture ESD stars by the present observations with \(K'\) band-limiting magnitudes of \(\sim 24.5\) mag. The estimated volume density due to these stars is \(2.5 \times 10^{-4} M_\odot\) pc\(^{-3}\). Even if the density of stars is extended uniformly to 30 kpc, the total mass is a little lower than 10\(^{13}\) \(M_\odot\), so that it could not be the majority of Galactic dark matter.

Another group of stellar components, significantly redder than \(M\) subdwarfs, is noticed in figure 14 in the \(J - K'\) color range from 1 to 1.5. It is likely that they correspond to the L-type dwarfs defined by Kirkpatrick et al. (1999), who have found very red stellar objects with \(J - Ks\) colors from 1.3 to 2.1 (practically the same color as the \(J - K'\) color). They have claimed that at least one third of L-type stars shows lithium absorption, and that
they are definitely in the category of brown dwarfs.

On the other hand, note that objects with $J - K'$ color of $\sim 0$ and small FWHM values are plotted in figure 14. In fact, they had a fairly large stellarity index (>0.8) in the $J$ band, but were dropped from identification due to faintness in the $K'$ band. The color is consistent with a T-type brown dwarf, GL229B (Nakajima et al. 1995; Kirkpatrick et al. 1999). However, it is necessary to prove show the nature of these L-type and T-type candidates through future multi-wavelength photometric and spectroscopic observations. Related discussions on the stellar members in SDF will be presented in Nakajima et al. (2000).

Finally, it is worth noting that the SDF sources have a connection to old, cool white dwarfs, which have recently drawn attention because they might account for most of the hidden baryonic mass of the Galaxy. Hodgkin et al. (2000) reported a cool white dwarf showing an extraordinary spectrum affected by the collision-induced absorption by hydrogen molecules, i.e., very red in the optical region but extremely blue at wavelengths longer than 1 $\mu$m, with a $J - K \sim -1.4$. In addition, Harris et al. (2000) identified LHS3250 as a very cool white dwarf with a $J - K$ of $-0.86$. A couple of old white dwarf candidates were also found with HDF frames taken at a 2-year interval, which are believed to be halo members as inferred from proper motion data (Ibata et al. 1999). These candidates were spectroscopically shown to be white dwarfs (Ibata et al. 2000).

These findings support the idea that very old white dwarfs could be responsible for a substantial portion, but not all, of the Galactic dark matter. In this connection, we have few stellar objects (only one below $J=25.0$) having stellarity index of 0.8 or larger, and with very blue color. This scarcity is consistent with the rough estimate by Hodgkin et al. (2000), who gave $\sim 7 \times 10^{-8}$ pc$^{-3}$ as a number density of white dwarfs with a typical mass of 0.5 $M_\odot$ in the solar neighborhood. If the absolute $J$ magnitude, $M_J$ of white dwarfs is assumed to be the same as WD 0346+246 of Hodgkin et al. (2000) with the detection limit being $m_J = 24.75$, then the viewable radial distance would be about 750 pc. The survey volume of the $2' \times 2'$ SDF field becomes $\sim 50$ pc$^3$, which is about a half of the volume of 109 pc$^3$ surveyed by Hodgkin et al.

In order to put a definite constraint on the number density of the white dwarf population, it is necessary to increase the survey region and also to perform an optical survey. Since the magnitudes in the optical bands are roughly the same as in the $J$ band ($\sim 25$ mag), such dwarf stars will be seen as optical images, by which the peculiar photometric color could be determined.

5. Summary

A deep near-infrared survey with the newly commissioned Subaru Telescope has been reported. We present two color data of $J$ and $K'$ bands as deep images, as well as diagrams, of galaxy number count vs. magnitude, of color vs. magnitude, and of size vs. color. i) It is found that slopes of galaxy number count plotted against the AB mag scale in both the $J$ and $K'$ bands are about 0.23 in the 22 to 26 AB mag range, which remain the same up to the faint end without a significant change. ii) From this result, we argue that the integrated surface brightness of faint SDF sources does not make an appreciable contribution to the extragalactic background light (EBL), or in other word, that the total EBL contributed by galaxies up to the faint end has nearly completely been resolved. However, measurements of diffuse EBL at this wavelength, if performed with enough precision, may pose a crucial cosmological issue regarding the light sources other than individual galaxies. iii) The color-magnitude diagram shows a fairly constant $J - K'$ color ($\sim 1.5$) up to about $K' \sim 23$ mag, although a scattered distribution, especially toward redder color, is noticed. iv) Intriguing objects with extremely red $J-K'$ colors are found in the SDF region. The listed objects are relatively bright (SN>5), and thus are safely classified as galaxies. The possibility of very high redshift objects, that is, candidates of Lyman break galaxies, are briefly discussed. v) A certain number of stellar sources have been identified, most of which are supposed to be M subdwarfs having colors of $J - K' \sim 0.6$. These are considered to be located at a median distance of about 2 kpc and are expected to provide samples for further studies of stars of this class for the purpose of examining a luminosity function as well as a contribution to the Galaxy mass. Brown dwarfs of the T-type may also be included in the detected source list. This should be confirmed by spectroscopic measurements.

Finally, it should be noted that the present near-infrared SDF survey work is the first step of the Subaru Deep Survey project planned to perform using other facility instruments of Subaru Telescope. For instance, follow-up observations of optical deep imaging with the optical spectrograph/camera called FOCAS (Kashikawa et al. 2000) will provide essential data to determine photometric redshifts of detected near-infrared sources. Objects as faint as $H=21.5$, or $J=22$ mag are well within the feasible range of spectroscopic observations with the OH-airglow suppression spectrograph (OHS), which has a unique capability of obtaining 1.1 to 1.8 $\mu$m spectra of 16 objects within a 3' field simultaneously, giving crucial information about the SDF sources.
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Table 1. Specifications and performance of CISCO.

| Item               | Description                  |
|--------------------|------------------------------|
| F.O.V.             | $2' \times 2'$               |
| Pixel scale        | 0.′116 pix$^{-1}$            |
| Filter             | $z, J, H, K', K$, NBF2.04, NBF2.12, NBF2.25 |
| Grism              | $zJ, JH, K$                  |
| Limiting magnitude | 22.6 mag ($K'$-band, 1 hour, S/N=5) |

Table 2. Observing log.

| Date (UT) | Band | Exposure time (sec) | Seeing FWHM(′′) | No. of frames | Total exp. time (sec) | Comment                |
|-----------|------|---------------------|-----------------|---------------|-----------------------|------------------------|
| 2/27/99   | $K'$ | 20                  | 0.35-0.80       | 96 x 3        | 5760                  | test observation       |
| 4/3/99    | $K'$ | 20                  | 0.40-0.70       | 96 x 2        | 3840                  |                        |
| 4/4/99    | $K'$ | 20                  | 0.35-0.60       | 96 x 2.75     | 5280                  |                        |
| 4/9/99    | $K'$ | 20                  | 0.70-1.10       | 96 x 0.5      | 960                   |                        |
| 4/25/99   | $K'$ | 20                  | 0.60-1.20       | 96 x 4        | 7680                  | flanking field 1-4    |
| 4/25/99   | $K'$ | 20                  | 0.80-1.20       | 96 x 2        | 3840                  | flanking field 5-6    |
| 4/29/99   | $J$  | 40                  | 0.45-0.65       | 48 x 2.5      | 4800                  |                        |
| 4/30/99   | $J$  | 40                  | 0.35-0.50       | 48 x 2.75     | 5280                  |                        |
| 5/2/99    | $J$  | 40                  | 0.40-0.65       | 48 x 6.5      | 12480                 |                        |
| 5/6/99    | $J$  | 40                  | 0.45-0.65       | 48 x 2        | 3840                  |                        |
| 5/7/99    | $J$  | 40                  | 0.35-0.50       | 48 x 2        | 3840                  |                        |
| 5/8/99    | $K'$ | 20                  | 0.35-0.55       | 96 x 1        | 1920                  |                        |
| 5/11/99   | $K'$ | 20                  | 0.25-0.60       | 96 x 6.5      | 12480                 |                        |
| 5/27/99   | $K'$ | 20                  | 0.20-0.30       | 96 x 3.5      | 6720                  |                        |
| 6/6/99    | $J$  | 40                  | 0.35-0.80       | 48 x 3        | 5760                  |                        |
| 6/7/99    | $K'$ | 20                  | 0.35-0.55       | 96 x 2        | 3840                  |                        |
| 6/7/99    | $J$  | 40                  | 0.45-0.75       | 48 x 2        | 3840                  |                        |
| 6/9/99    | $J$  | 40                  | 0.35-0.40       | 48 x 2        | 3840                  |                        |
| 6/20/99   | $K'$ | 20                  | 0.50-1.20       | 96 x 2        | 3840                  | flanking field 7-8    |
| 6/22/99   | $K'$ | 20                  | 0.40-0.65       | 96 x 1        | 1920                  | flanking field 8      |
Table 3. Corrected number counts

| Magnitude | $J$-band count | $J$-band error | $K'$-band count | $K'$-band error |
|-----------|----------------|----------------|-----------------|-----------------|
| 16.25     | 0.000e+00      | 0.000e+00      | 1.918e+03       | 1.931e+03       |
| 16.75     | 0.000e+00      | 0.000e+00      | 1.358e+02       | 5.118e+02       |
| 17.25     | 0.000e+00      | 0.000e+00      | 5.635e+03       | 3.293e+03       |
| 17.75     | 3.231e+01      | 2.500e+02      | 5.755e+03       | 3.338e+03       |
| 18.25     | 1.949e+03      | 1.942e+03      | 7.721e+03       | 3.869e+03       |
| 18.75     | 3.851e+03      | 2.725e+03      | 9.653e+03       | 4.326e+03       |
| 19.25     | 5.769e+03      | 3.354e+03      | 1.346e+04       | 5.100e+03       |
| 19.75     | 3.996e+03      | 2.776e+03      | 1.915e+04       | 6.111e+03       |
| 20.25     | 1.314e+04      | 5.044e+03      | 2.885e+04       | 7.513e+03       |
| 20.75     | 1.368e+04      | 5.162e+03      | 4.757e+04       | 9.647e+03       |
| 21.25     | 2.296e+04      | 6.705e+03      | 5.145e+04       | 1.006e+04       |
| 21.75     | 3.099e+04      | 7.789e+03      | 7.073e+04       | 1.187e+04       |
| 22.25     | 4.357e+04      | 9.255e+03      | 8.419e+04       | 1.307e+04       |
| 22.75     | 5.835e+04      | 1.070e+04      | 1.066e+05       | 1.488e+04       |
| 23.25     | 7.499e+04      | 1.224e+04      | 1.487e+05       | 1.873e+04       |
| 23.75     | 8.759e+04      | 1.333e+04      | 1.962e+05       | 3.129e+04       |
| 24.25     | 1.131e+05      | 1.524e+04      | 2.548e+05       | 5.648e+04       |
| 24.75     | 1.615e+05      | 1.905e+04      | 3.421e+05       | 1.031e+05       |
| 25.25     | 2.160e+05      | 2.949e+04      | 4.793e+05       | 2.214e+05       |
| 25.75     | 2.624e+05      | 5.623e+04      | —               | —               |
| 26.25     | 3.451e+05      | 1.227e+05      | —               | —               |

Table 4. $K'$-magnitude and color of extremely red objects.

| ID Number* | Position† (2000.0) | $K'$ | $J - K'$ |
|------------|-------------------|------|----------|
| 1          | 13°24′22″38″ +27°29′49″5″ | 20.91 (±0.05) | 2.97 (±0.14) |
| 2          | 13°24′22″39″ +27°29′01″7″ | 22.03 (±0.09) | 3.65 (±0.40) |
| 3          | 13°24′21″16″ +27°29′01″9″ | 21.99 (±0.05) | 2.81 (±0.20) |
| 4          | 13°24′22″84″ +27°30′08″4″ | 22.31 (±0.14) | 4.12 (±1.04) |

*ID numbers assigned to objects are from left to right in figure 13.
†Astrometry of these objects was made by the coordinates of an HST guide star found in the flanking field. The estimated accuracy is ±0″15.
Figure Captions.

Figure 1. The survey area of SDF overlaid on the Digitized Sky Survey (DSS) map. The near-infrared survey is performed in the $2' \times 2'$ region marked by a dashed square box. The surrounding region, which we call flanking fields, is also shown enclosed by the solid line square box.

Figure 2. $J$ band SDF image.

Figure 3. $K'$ band SDF image.

Figure 4. Two-color image composed from the $J$ and $K'$ band images. Image sizes are normalized to 0''.45 in FWHM.

Figure 5. Multiple simulations of photometric measurements for mock objects embedded in survey images. An enlarged diagram with numerical fractions in the 0.5 mag cells is shown in the upper right corner to show how the measured total magnitude distributed against the model sources. The lower panel shows diagrams of calculated completeness in both the $J$ (filled triangles) and the $K'$ band (filled circles).

Figure 6. Number count vs. magnitude diagram of the $J$ band. The number counts corrected for completeness are plotted with filled symbols, while the raw counts are open symbols. The circles, triangles, and squares denote total, isophotal, and aperture magnitudes, respectively.

Figure 7. Same as Fig. 6, but for the $K'$ band.

Figure 8. Galaxy number count vs. magnitude of the $J$ band. The data and authors of previous surveys are shown in the panel.

Figure 9. Same as figure 8 but for the $K'$ band.

Figure 10. AB magnitude plots of $J$, $H$, and $K'$ band data. Previous near-infrared surveys are also plotted for comparison.

Figure 12. Integrated flux of SDF sources (filled circles) in each magnitude bin. Fluxes of other survey data are also shown.

Figure 12. Color-magnitude relation for the SDF sources. Objects detected in both the $J$ and $K'$ bands are plotted by open circles. Objects detected either in the $J$ or $K'$ band are represented by “x” or “+” marks, respectively. Thin solid lines are the color change vs. magnitude for representative types of galaxy assuming a simple no-evolution model based on SED models of Yoshii & Takahara (1988) and Coleman, Wu, & Weedman (1980). Solid squares show the median color with standard deviation. Note that objects detected only in the $J$ or $K'$ band have been photometrically measured with same aperture sizes to determine $K'$ or $J$ band magnitudes, respectively, as explained in the text.

Figure 13. Examples of images of the four reddest objects found in the SDF. $J$-band images are shown in the upper row, and $K'$-band images are in the lower row.

Figure 14. FWHM vs. $J - K'$ color diagram. FWHM values are adopted from $K'$ band images. Open stars represent objects identified as stars on the basis of the proclaimed criteria (see text). Open circles are objects detected in both bands, while “x” and “+” marks represent objects selected only in the J-band and $K'$-band respectively.
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