THE MAHOROBA PROJECT — DEEP SURVEY WITH AN OPTICAL INTERMEDIATE-BAND FILTER SYSTEM ON THE SUBARU TELESCOPE

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ABSTRACT

We present a summary of the new optical intermediate-band filter system for the prime-focus camera, Suprime-Cam, on the Subaru telescope at Mauna Kea Observatories. We also discuss a future plan to promote a new deep survey with this filter system (the MAHOROBA project).

1. INTRODUCTION

Recent great progress in the observational astronomy have revealed that a large number of high-redshift galaxies can be accessible by continuum emission of galaxies (stellar continuum, thermal continuum from dust grains, or nonthermal continuum from plasma heated by supernovae) in a wide range of observed wavelengths between optical and radio (e.g., Williams et al. 1996, 2000; Lanzetta et al. 1996; Madau et al. 1996; Barger et al. 1998; Hughes et al. 1998).

Another important technique to probe high-z young galaxies is to search for strong emission-line (e.g., Lyα) galaxies. It has been often argued that forming galaxies at high redshifts experienced very luminous starbursts and thus they could be much brighter in line emission such as Lyα and [O II]λ3727 emission lines. However, the low-resolution spectroscopic capability of 8-m class telescopes is accessible only for galaxies with a magnitude brighter than \( B \sim 24.5 \) mag (e.g., Steidel et al. 1996a, 1996b). Therefore, even now, it is difficult to investigate properties of very faint galaxies with \( B > 25 \), most of which may be interesting high-z galaxies.

In order to improve our understanding of the nature of such faint galaxies, we would like to promote a new optical deep surveys with intermediate-band filters whose spectroscopic resolutions are significantly higher than those of typical broad-band filters. In this article, we present a short summary of the new optical intermediate-band filter system for the prime-focus camera, Suprime-Cam (Miyazaki et al. 1998), on the Subaru telescope (Kaifu 1998; Kaifu et al. 1998) at Mauna Kea Observatories. We also discuss a future plan to promote a new deep survey with this filter system (the MAHOROBA project).

2. THE FILTER SYSTEM

The Subaru intermediate-band filter (IBF) system consists of 22 filters with a spectral resolution of \( R = \lambda/\Delta\lambda \approx 23 \), covering a wavelength range between 3830 Å and 9900 Å (Table 1; see also Hayashino et al. 2000). The final specifications of these filters are summarized in Table 2. Their nice performance was already demonstrated by the wonderful image of the Ring Nebula M57 (Komiyama et al. 2000; see also Nature 401, 314).

In Figure 1, we show the transmission curves for all the IBFs. The merits of our IBF system are summarized below.

1) More reliable estimate of photometric redshifts of very faint galaxies: The accuracy of photometric redshifts using our IBF system is \( \sim 90\% \) (Shioya et al. 2001), being much higher than those using broad-band photometric information, i.e., \( \sim 60\% \) (e.g., Hogg et al. 1998). Therefore, our filter system enables us to investigate physical properties of faint galaxies down to 27AB and thus contribute to the understanding of cosmic star formation history as well as the large scale structure at high redshift.

2) More accurate estimate of SEDs of high-

\(^1\)MAHOROBA is an ancient Japanese word. The meaning of this word is “the best place” or “the most comfortable place”. Since the Subaru telescope must be a MAHOROBA for Japanese optical/infrared astronomers, we call our new deep survey program MAHOROBA.
**z galaxies:** Since the spectroscopic resolution of IBF system is \( R = 23 \), we will be able to investigate spectral energy distribution (SEDs) of high-z faint galaxies more accurately. Our data are also useful in investigating the SED of old (\( \sim 10^9 \) years old) galaxies at intermediate redshift, e.g., \( z \sim 1 \) (e.g., Dunlop et al. 1996; Cowie et al. 2001). Therefore, deep surveys with the present IBF system allow us to investigate the cosmic star formation history from high-z through intermediate-z to the present day unprecedentedly.

III) **More efficient capability of searching for strong emission-line objects:** Deep surveys with a narrow-band filter provide a powerful method to search for strong emission-line galaxies. Indeed, \( \sim 100 \) high-z Ly\( \alpha \) emitters have been found recently (Cowie & Hu 1998; Keel et al. 1999; Steidel et al. 2000). However, it is expected from the above recent surveys that a huge number of such strong emission-line sources have not yet been probed by the existing deep broad-band surveys because the majority of them have too faint continuum emission fluxes and thus they cannot be seen in broad-band images (see also Hu et al. 1999).

For Ly\( \alpha \) emitters whose continuum magnitudes are brighter than 27 AB (see section 3), we will be able to detect them surely by examining the continuum depression shorter than \( \lambda < \lambda_{\text{Ly}\alpha} \), which is an important characteristic of high-z Ly\( \alpha \) emitters. Even for Ly\( \alpha \) emitters whose continuum magnitudes are fainter than 27 AB, we will be able to detect them surely if their emission-line equivalent widths (EW) in the observed frame are larger than 200 \( \AA \).

It is here remembered that the existing narrow-band deep surveys were made for small selected volumes at high redshifts (e.g., \( \sim 10^9 h^{-3} \) Mpc\(^3 \)) where \( h = 100 h \) km s\(^{-1} \) Mpc\(^{-1} \)) and thus there is no systematic search for strong emission-line objects of a significantly large volume of the young universe. Thanks to the wide-field coverage of Suprime-Cam (34’ \( \times \) 34’), our survey can probe a volume of more than \( 10^9 h^{-3} \) Mpc\(^3 \) in a field.

Strong emission-line galaxies could be much more common at high redshift. If this is the case, it seems dangerous to investigate the cosmic star formation history solely using galaxies found in broad-band deep surveys, such as Lyman break galaxies (LBGs). This also reinforces the importance of deep surveys with our IBF system.

In summary, deep and wide-field imaging with the combination between this IBF system and Suprime-Cam on Subaru will contribute very much to the understanding of cosmic star formation history in the universe and the growth of large-scale structures in the universe.

3. **THE MAHOROBA PROJECT**

The 8-m class telescope facilities such as the W. M. Keck telescopes, VLTs, and Subaru have the greatest capability of probing high-z universe. Among the 8-m class telescopes, Subaru has a very unique merit; i.e., the wide-field prime-focus camera, Suprime-Cam, whose sky coverage is 34’ \( \times \) 34’. This instrument enables us to perform wide-field, deep imaging surveys in the optical.

However, in the 90’s, the Hubble Deep Field project (Williams et al. 1996) already brought us the very deep images of the universe down to 29AB. Even though its field is not so wide, we have learned so many things from this survey together with the HDF-S project (Williams et al. 2000). Therefore, simple deep imaging surveys with typical broad-band filters on the 8-m class telescopes will not give us a new impact even if we use Suprime-Cam on Subaru. We then believe that a new frontier will be high-spectral-resolution, deep imaging surveys. This is the main reason why we are now planning to promote a new deep survey program called “MAHOROBA” using the present IBF system on Subaru.

In this project, we will observe some blank sky fields such the Hubble Deep Field-North (Williams et al. 1996) and the Subaru Deep Field (Maihara et al. 2001). The limiting magnitude of this survey is tentatively set to be 27AB for each IBF. Our main aims are: i) to investigate the origin of reionization of the universe, and ii) to search for primeval (metal-free) galaxies, because there has been no such an attempt in the optical.

According to the big bang cosmology, our universe began 12-14 billion years ago. The universe was filled with hot plasma for the first 300,000 years (corresponding to redshift \( z \sim 1000 \)) and then the plasma recombined after that epoch. However, it is known that the universe (the intergalactic space) between redshift 0 and 5 is completely ionized. Therefore, our universe was reionized by some ionization sources between \( z \sim 1000 \) and \( z \sim 5 \) (i.e., the dark age: Rees 1996, 1999; see also Loeb & Barkana 2001). The origin of reionization of the universe has been in debate.
### Table 1
**The Subaru IBF System**

| IBF No. | Name   | Central Wavelength (Å) | Band Width (Å) | $z$(Lyα) |
|---------|--------|------------------------|----------------|----------|
| 1       | IBF392 | 3922                   | 193            | 2.22     |
| 2       | IBF409 | 4091                   | 201            | 2.36     |
| 3       | IBF427 | 4267                   | 207            | 2.51     |
| 4       | IBF445 | 4451                   | 220            | 2.66     |
| 5       | IBF464 | 4643                   | 230            | 2.82     |
| 6       | IBF484 | 4844                   | 240            | 2.98     |
| 7       | IBF505 | 5053                   | 250            | 3.16     |
| 8       | IBF527 | 5271                   | 260            | 3.33     |
| 9       | IBF550 | 5499                   | 270            | 3.52     |
| 10      | IBF574 | 5736                   | 280            | 3.72     |
| 11      | IBF598 | 5984                   | 295            | 3.92     |
| 12      | IBF624 | 6242                   | 310            | 4.13     |
| 13      | IBF651 | 6512                   | 325            | 4.36     |
| 14      | IBF679 | 6793                   | 340            | 4.59     |
| 15      | IBF709 | 7086                   | 340            | 4.83     |
| 16      | IBF738 | 7381                   | 340            | 5.07     |
| 17      | IBF768 | 7676                   | 340            | 5.31     |
| 18      | IBF797 | 7971                   | 340            | 5.56     |
| 19      | IBF827 | 8266                   | 340            | 5.80     |
| 20      | IBF856 | 8561                   | 340            | 6.04     |
| 21      | IBF907 | 9070                   | 410            | 6.46     |
| 22      | IBF965 | 9650                   | 500            | 6.94     |

### Table 2
**The Final Specifications for the IBF System**

| Item                                      | Specification                  |
|-------------------------------------------|--------------------------------|
| Clear aperture                            | 185 mm × 150 mm                |
| Peak transmittance ($T_{peak}$)           | > 70% (> 80% goal)             |
| Homogeneity of $T_{peak}$                 | < 5%                           |
| Ripple (valley/peak)                      | > 85%                          |
| Linear change (valley/peak)               | > 90%                          |
| CWL tolerance                             | < ±0.25 % of CW                |
| FWHM tolerance                            | < ±0.25 % of CW                |
| Bubble                                    |                                 |
| d < 0.1 mm                                | acceptable                     |
| d = 0.1-0.2 mm                            | ≤ 5 bubbles                    |
| d = 0.2-0.5 mm                            | ≤ 3 bubbles                    |
| d > 0.5 mm                                | Not allowed                    |
| Stain                                     | Not allowed                    |
but there is no firm answer even at present. Since galaxies could form under the ultraviolet background radiation responsible for the reionization, it is very important to investigate the origin of reionization.

However, observational properties of high-$z$ intergalactic space have been traditionally investigated by using quasar absorption-line systems as well as the so-called Gunn-Peterson test. Therefore, any information of this kind is indirect because neutral gas clouds are used in such studies. The MAHOROBA survey will be able to detect many faint emission-line objects between $z \approx 2$ and 7 and thus to investigate what sources are mainly responsible for the reionization of universe unambiguously.

It seems also worth noting that two very extended Ly$\alpha$ emission-line nebulae, Ly$\alpha$ blobs (LABs), have been found by Steidel et al. (2000); see also Francis et al. (2001). Their observational properties are summarized as below (we adopt an Einstein-de Sitter cosmology with a Hubble constant $H_0 = 100h$ km s$^{-1}$ Mpc$^{-1}$); 1) the observed Ly$\alpha$ luminosities are $\sim 10^{43}h^{-2}$ ergs s$^{-1}$, 2) they appear elongated morphologically, 3) their sizes amount to $\sim 100$ $h^{-1}$ kpc, 4) the observed line widths amount to $\sim 1000$ km s$^{-1}$, and 5) they are not associated with strong radio-continuum sources such as powerful radio galaxies. As for the origin of LABs, two alternative ideas have been proposed. One is that these LABs are superwinds driven by the initial starburst in galaxies because all the above properties as well as the observed frequency of LABs can be explained in terms of the superwind model (Taniguchi & Shioya 2000). The other idea is that LABs are cooling radiation from proto-galaxies or dark matter halos (Haiman, Spaans, & Quataert 2000; Fardal et al. 2001; Fabian et al. 1986; Hu 1992). Standard cold dark matter models predict that a large number of dark matter halos collapse at high redshift and they can emit significant Ly$\alpha$ fluxes through collisional excitation of hydrogen. These Ly$\alpha$ emitting halos are also consistent with the observed linear sizes, velocity widths, and Ly$\alpha$ fluxes of the LABs. Very recently, one of these Ly$\alpha$ blobs has been detected at submillimeter wavelengths, 450 $\mu$M and 850 $\mu$m (Chapman et al. 2001). Its rest-frame spectral energy distribution between optical and far-infrared is quite similar to that of Arp 220, which is a typical ultraluminous starburst/superwind galaxy in the local universe. Therefore, it is strongly suggested that the superwind model proposed by Taniguchi & Shioya is applicable to this Ly$\alpha$ blob (Taniguchi, Shioya, & Kakazu 2001). Since the blob is more luminous
in the infrared by a factor of 30 than Arp 220, it comprises a new population of hyperwind galaxies at high redshift. It is expected that such unknown objects will be found in our survey.

We human beings have not yet found very young, primeval galaxies which do not contain heavy elements. This suggests that any material was once polluted by so-called Population III objects formed at $z \sim 10^{-15}$. Actually we know that broad emission-line gas clouds associated with high-z quasars ($z > 5$) are already polluted chemically (Hamann & Ferland 1999). However, a question arises here; “have we already made very deep surveys dedicated to finding such primeval galaxies ?”. We think that the answer is “no” because there has been no efficient tool for this purpose; note that we need wide-field, very deep imaging surveys with narrower-band filters. It is known that metal-free, population III stars have higher effective temperatures and thus they show very strong He\text{\textit{ii}}$\lambda 1640$ emission line without any metallic lines such as C\text{iv}, and so on (e.g., Tumlinson, Girouz, & Shull 2001 and references therein). This means that searches for strong He\text{\textit{ii}} emission-line sources may lead to the discovery of primeval galaxies. Our survey will be also dedicated to this issue.

This project will be an unprecedented trial toward the dark age from the side of the optical astronomy. Now we are ready to go the realm of high-redshift blizzard.

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REFERENCES

Barger, A., Cowie, L. L., Sanders, D. B., Fulton, E., Taniguchi, Y., Sato, Y., Kawara, K., & Okuda, H. 1998, Nature, 394, 248

Chapman, S. C., Lewis, G. F., Scott, D., Richards, E., Borys, C., Steidel, C. C., Adelberger, K. L., & Shapley, A. E. 2001, ApJ, 548, L17

Cowie, L. L., & Hu, E. M. 1998, AJ, 115, 1319

Cowie, L. L., et al. 2001, ApJ, 551, L9

Dunlop, J., Peacock, J., Spinrad, H., Dey, A., Jimenez, R., Stern, D., Windhorst, R. 1996, Nature, 381, 581

Fabian, A. C., Arnaud, K. A., Nulsen, P. E. J., & Mushotzky, R. F. 1986, ApJ, 305, 9

Fardal, M. A., Katz, N., Gardner, J. P., Hernquist, L., Weinberg, D. H., & Davé, R. 2001, ApJ, in press (astro-ph/0007205)

Francis, P. J., et al. 2001, ApJ, 554, 1001

Haiman, Z., Spaans, M., & Quataaet, E. 2000, ApJ, 537, L5

Hamann, F., & Ferland, G. 1999, ARA&A, 37, 487

Hayashino, T., et al. 2000, SPIE, 4008, 397

Hogg, D. W., et al. 1998, AJ, 115, 1418

Hu, E. M. 1992, ApJ, 391, 608

Hu, E. M., McMahon, R. G., & Cowie, L. L. 1999, ApJ, 522, L9

Hughes, D., et al. 1998, Nature, 394, 241

Kaifu, N. 1998, SPIE, 3352, 14

Kaifu, N., et al. 2000, PASJ, 52, 1

Keel, W. C., Cohen., S. H., Windhorst, R. A., & Waddington, I. 1999, AJ, 118, 2547

Komiyama, Y., et al. 2000, PASJ, 52, 93

Lanzetta, K. M., Yahil, A., & Fernandez-Soto, A. 1996, Nature, 381, 759

Loeb, A., & Barakana, R. 2001, ARA&A, in press (astro-ph/0010467)

Madau, P., Ferguson, H. C., Dickinson, M. E., Giavalisco, M., Steidel, C. C., & Fruchter, A. 1996, MNRAS, 283, 1388

Maihara, T. et al. 2001, PASJ, 53, 25

Miyazaki, S., Sekiguchi, M., Imi, K., Okada, N., Nakata, F., & Komiyama, Y. 1998, SPIE, 3355, 363

Rees, M. J. 1996, The Hubble Space Telescope and the High Redshift Universe, 115

Rees, M. J. 1999, After the Dark Age: When Galaxies were Young, 13

Shioya, Y., et al. 2001, in preparation

Steidel, C. C., Giavalisco, M., Dickinson, M., & Adelberger, K. L. 1996a, AJ, 112, 352

Steidel, C. C., Giavalisco, M., Pettini, M., Dickinson, M., & Adelberger, K. L. 1996b, ApJ, 462, L17

Steidel, C. C., Adelberger, K. L., Shapley, A. E., Pettini, M., Dickinson, M., & Giavalisco, M. 2000, ApJ, 532, 170

Taniguchi, Y., & Shioya, Y. 2000, ApJ, 532, L13

Taniguchi, Y., Shioya, Y., & Kakazu, Y. 2001, ApJ, in press (astro-ph/0110355)

Tumlinson, J., Girouz, M. L., & Shull, M. 2001, ApJ, 550, L1

Williams, R. E., et al. 1996, AJ, 112, 1335

Williams, R. E., et al. 2000, AJ, 120, 2735