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**Subaru Instruments, Science Achievements, and Future Plans**

### **Abstract**

*The outline, history, specific features and operational status of the 8.2 m Subaru Telescope are reviewed. The currently available instrument package consists of SuprimeCam, FOCAS, HDS, IRCS, COMICS and MOIRCS, covering a wide range of wavelength-spectral resolution space for the instruments. AO188 is also available with natural guide stars for operation. Among the many science achievements of the Subaru Telescope, studies of high redshift Lyman alpha emitters using SuprimeCam to elucidate the cosmic re-ionization history and studies of the GRB-SNe connection using FOCAS spectropolarimetry are mentioned as successful examples that have exploited the full capability of these unique instruments. Further instruments under construction or at the final test stage are FMOS, LGSAO188, HiCIAO and HSC.*

*Subaru will strengthen its observational capabilities at its unique prime focus. In addition to HSC, which produces an image covering 1.5 degrees, a possible new instrument could be a wide field multi-object spectrograph for cosmology and galactic archaeology if funds become available. These unique instruments would also serve for isolating key targets to be observed by ELTs.*

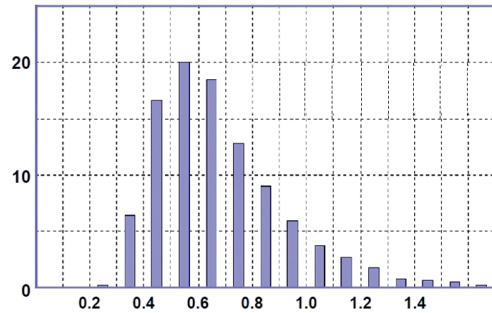
**Keywords:** *Subaru Telescope, instruments, performance, future plan*

## 1. Introduction

The 8.2 m Subaru Telescope atop Mauna Kea (Figure 1), Hawaii, received its engineering first light in December 1998. It has been available to the astronomy community since December 2000. Details of the telescope system and its performance can be found in review papers<sup>1,2</sup>. The best image size ever confirmed is 0."2, both in the optical and near infrared, and the median seeing size is about 0."6, as shown in Figure 2.



**Figure 1. Subaru Telescope at the summit of Mauna Kea.**

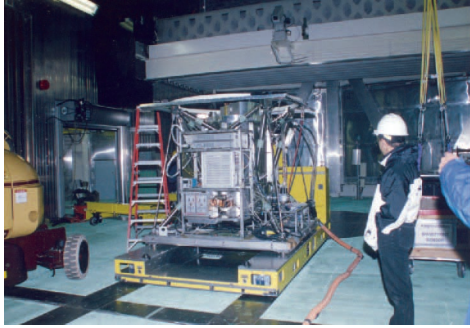


**Figure 2. Subaru seeing size statistics.**

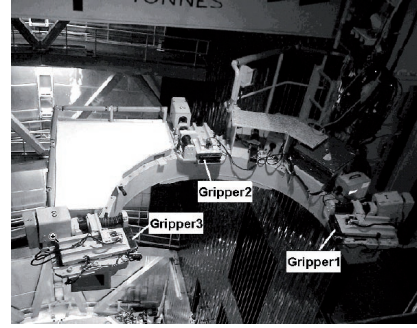
The first generation scientific instruments consisted of :

- 1) the SUbaru PRIME-focus CAMera (Suprime-Cam)<sup>3</sup>,
- 2) the InfraRed Camera and Spectrograph (IRCS)<sup>4,5</sup>,
- 3) the Faint Object Camera And Spectrograph (FOCAS)<sup>6</sup>,
- 4) the OH airglow Suppression spectrograph (OHS)<sup>7</sup> and its camera module (CISCO)<sup>8</sup>,
- 5) the High Dispersion Spectrograph (HDS)<sup>9</sup>,
- 6) the Cassegrain 36-element Adaptive Optics (AO36)<sup>10</sup>,
- 7) the COoled Mid Infrared Camera and Spectrograph (COMICS)<sup>11</sup>,
- 8) the Coronagraphic Imager with Adaptive Optics (CIAO)<sup>12</sup>.

All these instruments received their first light by the end of 2000. Four Cassegrain instruments - FOCAS, IRCS, CIAO, and COMICS - were stored at four standby ports on the observing floor and they can be tested there, if necessary, with connection to the network system. The Cassegrain instruments, weighing 2 tons each, can be exchanged by using the semi-automatic instrument exchanging system CIAX<sup>13</sup> in about an hour during the daytime (Figure 3). The Suprime-Cam and other secondary mirrors are stored on the top unit floor and can also be exchanged by using the top unit exchange system (Figure 4) in 6 hours during the daytime<sup>1</sup>. During the first 28 months between 2000 May and 2002 August, the telescope was operational for 26 months. The top unit was exchanged 56 times and the instruments were changed



**Figure 3 Cassegrain Instrument Automatic eXchanger.**



**Figure 4 Top Unit Exchanger system**

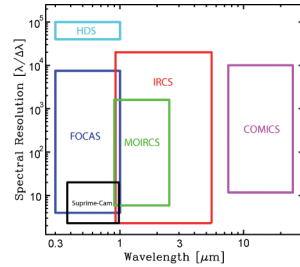
89 times, corresponding to roughly 2.2 top unit exchange operations and 3.4 instrument exchange operations per month. Note that more than an average of 70% of telescope time is used for science observations.

Suprime-Cam, covering a 34' x 27' field of view with an unvignetted area of 30' diameter, with ten 4k x 2k CCDs, has been the most heavily used of the Subaru instruments. In good seeing, the wide field prime focus corrector provides a superb image quality of 0.''3 even near the edge of the field. Standard sets of broad band filters B, V, R, Ic, g', r', i', and z' and a number of narrow band filters are available with some restriction on usage. Suprime-Cam has an automatic filter exchanger that can hold up to ten filters. The images taken during the first light campaign of Suprime-Cam were shown to be as deep as those taken by WFPC2 on the HST.

Table 1. List of the current and near future Subaru instrument suite

Acronym	Full Name	Focus	FL	Status
1 Suprime-Cam	Subaru Prime Focus Camera -	Pr	07/00	Av
2 IRCS	Infrared Camera and Spectrograph	IR Ns	06/00	Av
3 FOCAS	Faint Object Camera And Spectrograph	Cs	03/00	Av
4 HDS	High Dispersion Spectrograph	Opt Ns	08/00	Av
5 COMICS	Cooled Mid-Infrared Camera and Spectrograph	Cs	01/00	Av
6 MOIRCS	Multi-Object Infrared Camera and Spectrograph	Cs	09/04	Av
7 LGSAO188	Laser Guide Adaptive Optics system	IRNs	02/09*	Av/Con
8 FMOS	Fiber Multi-Object Spectrograph	Pr	-	Con
9 Hyper Suprime	Hyper Suprime-Cam	Pr	-	Con-
10 HiCIAO	High-Contrast Coronagraphic Imager for Adaptive Optics	IRNs	-	Con

Av: Available, Con: under Construction, \* NGS AO available



**Figure 5. Wavelength – spectral resolution domain coverage of Subaru instruments.**

OHS, CISCO, and AO36 were decommissioned by 2009 and CIAO was removed from an open use package. Figure 5 shows the region in the wavelength—spectral resolution plane covered by the current suite of instruments. All the instruments employ closed-cycle refrigerators to cool the detector. No liquid nitrogen is used.

Five second generation new instruments:

- 9) the Multi-Object InfraRed Camera and Spectrograph (MOIRCS)<sup>14,15</sup>,
- 10) the Laser Guide Star Adaptive Optics (LGSAO188)<sup>16</sup>,
- 11) the Fiber Multi-Object Spectrograph (FMOS)<sup>17-19</sup>,
- 12) HiCIAO<sup>20,21</sup>,
- 13) Hyper Suprime Cam (HSC)<sup>22,23</sup>

will join the Subaru instrument suite. MOIRCS is a fully cryogenic double beam multi-object infrared camera and spectrograph constructed as a joint project between the NAOJ and Tohoku University. The imaging mode has been in service since S05B, and the MOS mode became available from S06B, operated with a natural guide star, has been available for open use since S09A. Table 1 gives an updated list of the current and near future Subaru instrument suite.

## 2. Science Achievements

By November 2008 536 refereed papers based on observations made with the Subaru Telescope had been published, for which a total of 13,637 citations had made by 27 July 2009. In addition 630 proceeding papers were published for the same period. These include many original studies of scientific significance. Let me introduce here just two cases, in which I think the unique properties of Subaru instruments led to successful findings.

The first example is the search for high redshift Lyman alpha emitters (LAEs). The Subaru Deep Field survey<sup>24</sup> was designed to probe galaxy populations at high redshifts by making deep imagings at B, V, R, I', z' to derive photometric redshift estimates and luminosity functions for galaxies at various redshifts. In addition to these broad band images, several narrow band filter images were designed to isolate emission line galaxies. For example, the NB711, NB816 and NB921 filters can pick

up galaxies with LAEs at redshift 4.8, 5.7, and 6.6, respectively. The spectra of these candidate galaxies were obtained by FOCAS and Keck DEIMOS and a large fraction of the photometric candidates was confirmed to be the real LAEs. The Subaru Deep Field survey used these narrow band images to derive the LAE luminosity functions<sup>25,26</sup> at these redshifts and found a significant decline in the population at their bright end from redshift 5.7 to 6.6<sup>26</sup>.

A further survey using NB973 to probe LAEs at redshift 7.0 yielded only one object (Figure 6,7,8), leading to the discovery of the most distant galaxy with redshift confirmation<sup>27</sup>. Table 2 shows the top ten list of most distant galaxies with published redshift measurements. Note here that the lack of LAEs at redshifts between 6.7 and 6.9 doesn't imply the absence of galaxies. This list reflects the result of surveys made only at redshift 6.6 and 7.0. One feature to be noted in this table, however, is

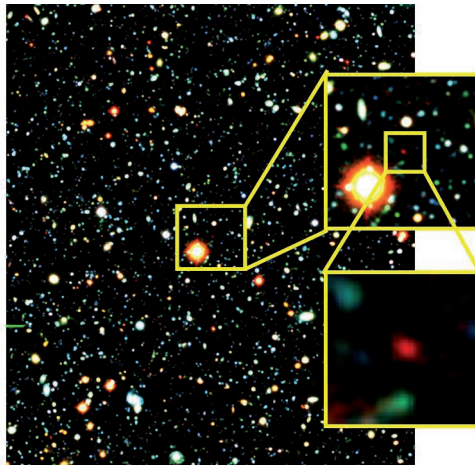


Figure 6. The most distant galaxy IOK-1 with redshift  $z=6.964$ , discovered among 41,533 objects detected in a 15 hour exposure.

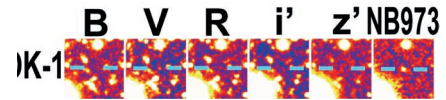


Figure 7. IOK-1 was isolated as a candidate object visible only in the image taken with a narrow band filter with central wavelength 973 nm and band width 22 nm but not in other images taken at shorter wavelengths.

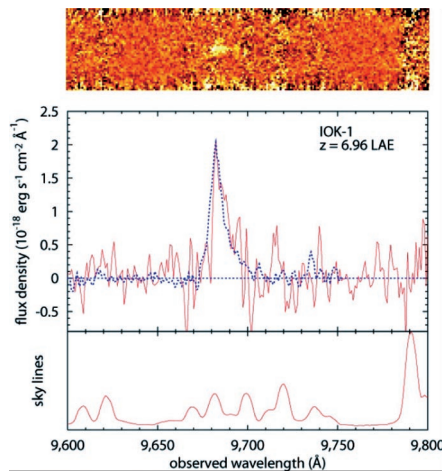
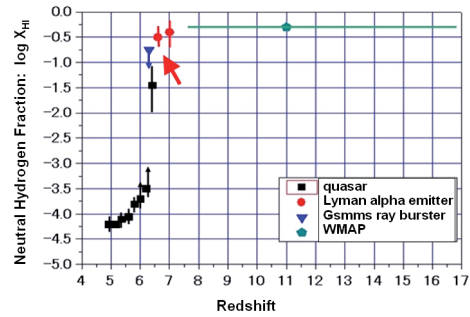


Figure 8. Spectroscopic follow-up observations clearly showed Lyman alpha emission line at 968 nm with an asymmetric line profile that matches the average line profile of Lyman alpha emitters observed at redshift 6.6.

Rank	ID	Coordinates	Redshift	0.1Gyr	Paper	Date
1	IOK-1	J132359.8+272456	6.964	128.8	Iye et al.	Sep. 14, 2006
2	SDF ID1004	J132522.3+273520	6.597	128.2	Taniguchi et al.	Feb. 25, 2005
3	SDF ID1018	J132520.4+273459	6.596	128.2	Kashikawa et al.	Apr. 25, 2006
4	SXDF Himiko	in SXDS field	6.595	128.2	Ouchi et al.	Jul. 25, 2008
5	SDF ID1030	J132357.1+272448	6.589	128.2	Kashikawa et al.	Apr. 25, 2006
6	SDF ID91163	J132343.4+272954.5	6.587	128.2	Kashikawa et al.	Feb. 2009
7	SDF ID91988	J132342.2+272644.5	6.587	128.2	Kashikawa et al.	Feb. 2009
8	SDF ID71101	J132450.7+272159.7	6.587	128.2	Kashikawa et al.	Feb. 2009
9	SDF ID1007	J132432.5+271647	6.580	128.2	Taniguchi et al.	Feb. 25, 2005
10	SDF ID1008	J132518.8+273043	6.578	128.2	Taniguchi et al.	Feb. 25, 2005

Table 2. Top ten highest redshift galaxies with published redshift measurement. Note that the surveys are made at redshifts 6.6 and 7.0.

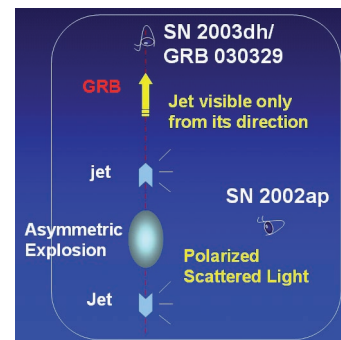
**Figure 9.** Logarithmic fraction of neutral hydrogen. Gunn-Peterson tests of quasars at  $z < 6.4$  indicate the completion of cosmic re-ionization by  $z \sim 6$ . Recent assessments comparing the luminosity functions of LAEs at  $z = 5.7, 6.6$  and  $7.0$  indicate the presence of residual neutral hydrogen at  $z = 6.6$  and  $7.0$ . Measurement of the electron scattering of microwave background radiation indicates cosmic re-ionization at around  $z \sim 11$ . These disparate facts seem to be piece together to reveal the cosmic dawn.



that the SDF survey confirmed only one LAE at redshift of 7.0 while tens of LAEs were detected at redshift 6.6. Although the limiting magnitude for the survey at redshift 7.0 is slightly shallower than that at redshift 6.6, this decrease in the LAE population from redshift 6.6 to 7.0 strengthens the previous finding of a declining observable LAE population at higher redshifts.

Since such a decrease in the LAE population from redshift 5.7 through 6.6 to 7.0 is seen only at Lyman alpha emission but not in the UV continuum close to the Lyman alpha emission, this is unlikely to reflect the evolution of primordial galaxies during this period. Instead, this decrease towards higher redshifts can be explained by the increasing fraction of neutral hydrogen towards higher redshift. The SDF team interprets this as evidence for late cosmic re-ionization. The WAMP result implies that cosmic re-ionization could have taken place at redshift  $10.9^{+1.428}$ , if this event was an instantaneous one. Subaru's possible witnessing of the final phase of cosmic re-ionization implies that the cosmic re-ionization process was a slow and inhomogeneous process. Figure 10 shows the implied fraction of the cosmic neutral hydrogen as a function of redshift.

**Figure 10.** Conceptual drawing showing the geometry of core-collapse type supernovae (hypernovae) having an asymmetric explosion with relativistic jets. When such an explosion is observed from the directions where the jets point, one can see a long-burst GRB and its afterglow showing no polarization. On the other hand if such an explosion is observed sideways, one does not see the GRB although one may be able to detect the polarized and scattered light from the jets.



A second example of Subaru science achievements is the study of GRBs and hypernovae by using the spectro-polarimetric observations. Spectropolarimetric observations of SN2002ap<sup>29,30</sup> elucidated the presence of a polarized component whose spectrum resembles that of the supernova but Doppler shifted by about 11% of the speed of light. SN2002ap is ascribed to a core-collapse type Ic supernova for which no GRB counterpart was identified. On the other hand observations of SN2003dh confirmed that not just the position but also the date of explosion, as estimated from



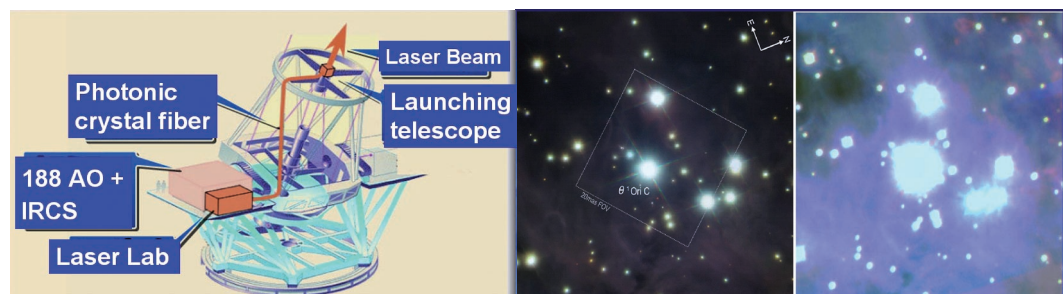
the evolving spectral features, of this SN coincide with those of GRB030329<sup>31</sup>. The spectra suggested a core-collapse type supernovae and no evidence for the presence of the scattered light component was confirmed. These findings, together with theoretical model predictions, led to the picture that core collapse type Ic supernovae generally have energetic asymmetric explosions with a pair of relativistic jets at their pole directions. When such an explosion is observed from the directions of jets, one can first see them as gamma ray bursts (GRBs) while the later optical observations of afterglows do not show a polarized component because of their axisymmetric view. On the other hand, when these objects are observed sideways, GRBs are not visible due to large angle between the relativistic beaming and the lines of sight. Although the beamed jets are not directly seen, one can see the scattered light from these jets as polarized light redshifted with respect to the star due to the jet motion. Further spectroscopic studies also show the asymmetric explosion in the emission line profiles<sup>32,33</sup>.

### 3. New Instruments and Future Plans

In this section, let me touch on new instruments that are under construction or in the test phase.

#### 3.1 Laser Guide Star Adaptive Optics (LGSAO) <sup>16</sup>

Construction of a new AO system with 188 sensing and control elements, five times in number more than the former 36 element Cassegrain system, has been available at the IR Nasmyth focus since 2009. The final tests for a laser guide star system is under way to increase the sky coverage. An all solid-state sodium laser produced by mixing two YAG lasers was successfully developed in collaboration with RIKEN.



**Figure 11. (a) Left: Layout of the laser, relay optical fibre, laser launching telescope, 188-element adaptive optics and instruments of LGSAO. (b).Right: Images of the Orion Trapezium, with (centre) and without (right) AO.**

A photonic crystal optical fibre to avoid non-linear scattering of the high power laser is developed to relay the laser beam to the launching telescope (Figure 11a). Figure 11b shows the first light image taken with AO188 without a laser guide star in 2006 and the image 8 the same object taken in 1999 without AO. It is clearly seen

that the AO improved the point spread function from 0.6 arcsec to 0.06 arcsec. Upgraded IRCS and HiCIAO are the instruments to be used in conjunction with the 188 element LGSAO.

Figure 12 shows one night when Subaru, Keck and Gemini launched their laser beams simultaneously. Although it reminds us of a “star wars” scenario, astronomers on Mauna Kea are collaborating to establish a system to control laser guide star observations so that the laser beams do not interfere other observations. The lasers are shut down when there is a risk of the laser beam being intercepted by aeroplanes or satellites flying above the mountain. An automatic control system using an IR camera to detect aeroplanes is being tested but for the moment we employ plane spotters while operating LGSAO.



Figure 12. Three laser beams shot from Subaru, Keck and Gemini.

### 3.2 High-Contrast Coronagraphic Imager for Adaptive Optics (HiCIAO)<sup>20,21</sup>

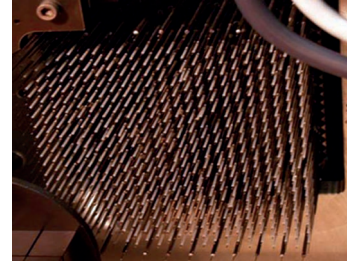
HiCIAO is a coronagraphic simultaneous differential imager to be placed at the Nasmyth platform under construction in collaboration with IfA, UH. HiCIAO consists of the cryogenic camera part and the non-cryogenic pre-optics part and designed as a flexible, experimental instrument to develop new technologies. A big project, SEEDS project, to search for extrasolar planets using this instrument started from S09A.

### 3.3 Fiber Multi-Object Spectrograph (FMOS)<sup>14-16</sup>

FMOS is a fibre multi-object spectrograph for the J and H bands to be mounted at the prime focus for spectroscopic observation of up to 400 objects in a 30' field (Figure 13). The prime focus unit with an infrared corrector was fabricated and tested on the telescope. Two sets of Echidna under fabrication at the Anglo-Australian Observatory (AAO), each having 200 fibre head positioners (Figure 14), are installed in the focal plane unit. The Echidna picks up target objects and relays the sampled light to the infrared spectrographs. Two of the infrared spectrographs were built at Kyoto University and in the UK. The commissioning of FMOS began in



**Fig. 13. Prime focus corrector for FMOS**

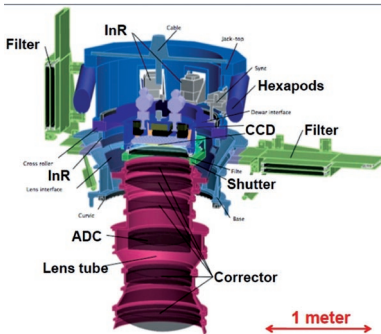


**Fig.14 Fibre spine heads of Echidna. Fibre positioner.**

2007. The engineering test has shown rather high scattered light within the instrument and work is being carried out to overcome of problem.

### 3.4 Hyper SuprimeCam <sup>22,23</sup>

Hyper SuprimeCam (HSC) is a third generation instrument now under construction (Figure 15). It will cover a 1.5 degree field of view. For installing this massive instrument, significant modification of the telescope structure, including the top-end unit, is necessary. The HSC, expected to have its first light in 2013, will be a unique survey instrument for studying the dark energy through the baryonic acoustic oscillation in the distribution of galaxies, and a large scale consortium to enable such a survey is planned in collaboration with Princeton University.



**Figure 15. Hyper SuprimeCam under construction. First light is expected at 2013.**

HSC will also be a powerful instrument to extend current frontiers to survey high redshift LAEs and Lyman break galaxies. As a unique wide field and deep imaging camera for the ELT era, HSC will serve to isolate faint and rare objects to be closely studied by ELTs.

### 3.5 Hyper FMOS

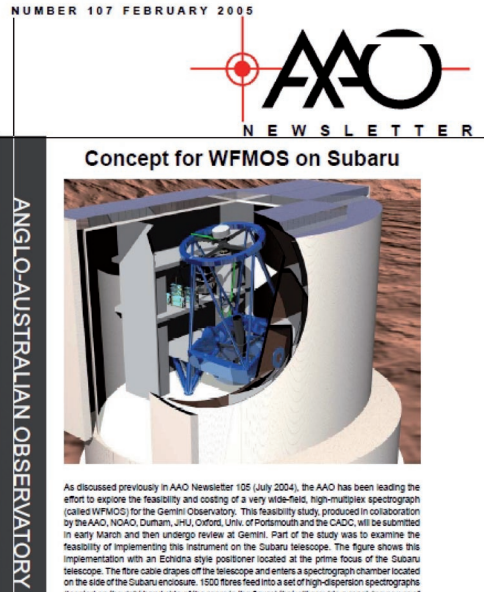
Assuming the availability of a new prime focus that can accommodate massive instruments, the Gemini group made a study for Wide-field Fiber-fed optical Multi-Object Spectrograph (WFMOS) under the ASPEN initiative (Figure 16). Such an instrument, together with HSC, will make the Subaru prime focus capability an

**Figure 16. WFMOS conceptual study by the Gemini AURA initiative.**

extremely unique feature among 8-10 m class telescopes. By establishing a large sample of galaxies with spectroscopic redshift measurements, one can draw the 3-dimensional distribution of galaxies to study the evolution of galaxy assembly. It took about 2 years for the Japanese community to nurse this concept for acceptance as a potential strong plan for the future. Although the Gemini board decided to abandon this plan in May 2009, NAOJ, instead, starting to seek finance to revive this instrument concept.

### 3.6 Subaru in the ELT era

The TMT board announced its decision to choose the 13 North site of Mauna Kea as the first choice to construct the TMT (Figure 17). This is good news for the NAOJ, which has longed to join the TMT on Mauna Kea. A new instrument package plan for the decade 2010 clearly foresees the importance of the wide field capability of



**Figure 17. The TMT on Mauna Kea**

Science with the 8-10m telescopes in the era of the ELTs and the JWST

the Subaru telescope with a synergy to serve as a pathfinder telescope for the TMT. Japan's community regards the international coordination and collaboration to share the instruments for 8-10 m class telescopes as a mandatory policy for the ELT era to keep the observatories in the forefront

#### 4. Acknowledgement

First of all, I would like to extend my sincere and respectful congratulations to the GTC consortium for inaugurating a superb telescope. This visit is actually my fourth visit to this island. I first came to La Palma back in 1990 looking for a site for Japanese 8 m telescope, later named the Subaru Telescope. My second visit was in 1995, when the Spanish community invited several foreign astronomers involved with large telescopes to review the Spanish large telescope project. I recall Jerry Nelson, the father of the GTC, making a persuasive argument at that time to convert the Spanish community from an 8 m meniscus mirror to a segmented primary. The brave decision of the Spanish community to adopt a segmented mirror concept led to today's great success. My third visit was in 1997 to carry out half a night of observation on the WHT of a high redshift galaxy candidate at  $z \sim 3.2$ , which ended up without a result due to adverse weather. This time, twelve years since my last visit, I am deeply impressed not only by the GTC but also by the growth of the entire observatory.

I would like to thank the LOC and SOC for inviting me to give a talk at this unforgettable conference and wish the GTC community all the best for the future.

Regarding the present paper describing the Subaru Telescope, readers are encouraged to obtain the most recent information from <http://www.naoj.org>. The author is grateful to all the Subaru staff members and the group members of individual instrument development. All the credit should go to those people who actually made the sophisticated telescope and its instruments a working reality and any blame for errors or biased statements in the present paper should be ascribed to the author.

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