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THE NEXT GENERATION CFHT

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ABSTRACT

The 3.6m Canada-France-Hawaii telescope (CFHT) saw first light in 1979. Since that time, it has proven to be one of the world's most versatile astronomical research facilities, enabling its users to make fundamental contributions to a remarkably wide range of scientific topics, including the properties of the outer solar system; exoplanet surveys; AGNs, quasars and supermassive black holes; high-redshift supernovae; the chronology of halo formation; stellar structure, evolution and abundances; galaxy evolution; structure formation; the nature of dark matter and dark energy; and the history of cosmic star formation. We briefly review the essential features of the CFHT site, telescope and partnership that have made it such a successful research facility for more than 30 years, and critically evaluate its future in the coming decades. The conclusion is that CFHT — which is facing increasingly stiff competition from newer, larger, telescopes — will be unable to maintain its position as a forefront facility unless the partners embark upon a bold plan to upgrade to its performance and capabilities.

We propose that the present CFHT be upgraded by ∼2020 to a 10m telescope (installed on the existing pier) equipped with a wide-field, highly multi-plexed spectrograph (i.e., a FOV ~ 1.5 deg^2 and $N_{\rm spec} \approx 3200$ fibers). This "next generation" CFHT would allow astronomers from the partnership to take a leadership role in addressing two key scientific questions of the coming decade — the measurement of the equation of state of the universe and the reconstruction of the formation history of the Milky Way. At the same time, it would provide a powerful research tool that would serve a wide user base, allow the partners to leverage observations from JWST, ALMA, LSST, WFIRST, GAIA, TMT and E-ELT, and, potentially, to gain access to other, complementary facilities.

Subject headings: telescopes – instrumentation – techniques

1. INTRODUCTION

CFHT is a facility that is jointly operated by Canada (through the Herzberg Institute of Astrophysics), France (through the Centre National de la Recherche Scientifique) and the University of Hawaii. The 3.6m telescope began operations in 1979, situated on the north end of the Mauna Kea summit ridge at an altitude of 4204 m. This location is regarded as perhaps the best astronomical site in the world, enjoying outstanding atmospheric stability (i.e., a median seeing of the free atmosphere of $0\farcs4$ with a 10th percentile quality of $0\farcs25$), low precipitable water vapour (median ≈ 0.9 mm) and a high percentage of useable nights (≈ 80% annually).

1.1. *Best in the World: 1979–1993*

Recognizing the extraordinary quality of the site, the CFHT partners quickly moved to capitalize on this unique strength, pioneering methods to reduce "dome seeing" and develop tip-tilt systems, active optics and higher-order adaptive optics systems to improve image quality — all of which have now become standard practices for astronomical facilities. Thanks to these technical innovations, CFHT users in the 1980s and early 1990s carried out transformational research in stellar, Galactic, and extragalactic astrophysics. Indeed, it can probably be said that CFHT was the "best" optical telescope in the world from 1979 to ∼1993, when the refurbished Hubble Space Telescope (HST) and 10m Keck I telescope began routine observations.

1.2. *Best in Class: 1993–2010*

Recognizing the stiff competition from HST, Keck, and an entire generation of 6.5-10m class telescopes that would begin to appear in the late 1990s, CFHT focused on the development of powerful instruments that gave it unique capabilities for a telescope of intermediate size. Notable instruments from this period include Gecko, MOS-SIS, OASIS and the AOB, as well as a succession of ever-larger CCD cameras: e.g., FOCAM, MOCAM and CFH12K. As the 6.5-10m telescopes established themselves as the forefront *spectroscopic* instruments, CFHT remained on the cutting edge of astrophysical research by focusing on high-resolution and wide-field imaging.

For the next decade or so, CFHT was arguably the world's premier telescope *in the 4m class*, although it must be noted that some other telescopes of comparable size also enjoyed considerable success by developing other unique capabilities (most notably the 3.9m AAT, which emphasized wide-field spectroscopic surveys, and the ESO 3.6m, which focused on the search for extrasolar planets). CFHT itself moved partially in this direction in the mid-2000s with the introduction of a reduced suite of three instruments (MegaCam, ESPaDOnS, and WIRCam) that aimed for a high level of impact through a combination of unique capabilities and a larger number of nights dedicated to ambitious surveys. The CFHT Legacy Survey, in particular, demonstrated this approach to be an highly effective one, and in 2008,

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four new Large Programs were initiated: NGVS, PandAS, MiMeS and MaPP.

1.3. *The End of an Era*

As we shall discuss below, the competition facing CFHT will grow dramatically in the coming decade. A number of exciting proposals for new instruments (that would be available around 2015) are presently being considered by the CFHT communities. These include GYES (a wide-field, 500-fiber optical spectrograph), SITELLE (a wide-field Fourier transform spectrometer), SPIRou (a near-IR, high-resolution spectrograph and spectropolarimeter) and IMAKA (a wide-field, GLAO-corrected mosaic camera equipped with orthogonal transfer CCDs). The emphasis on *wide field* capabilities and/or *spectroscopy* is clear, and there is no doubt that each of these instruments would offer a new capability to CFHT users. Thus, these instruments continue the heritage of ingenuity that the CFHT partners have shown over the past 30 years adapting to the ever changing astronomical landscape.

At the same time, we believe that the era in which CFHT — with its now modest aperture of 3.6m — has remained at the forefront of astronomical research facilities, is drawing to a close *unless the partnership make its most ambitious changes yet.*

As Table 1 shows, other 4m-class telescopes (WIYN, VISTA) have, like CFHT, aggressively pursued the development of wide-field imaging capabilities at optical and IR wavelengths, and several new facilities (PS1, PS2, Skymapper) will soon outperform CFHT in terms of areal and temporal coverage. A particularly strong challenge will come as early as 2012 from the 8.2m Subaru telescope, whose Hyper-SuprimeCam (HSC) will outperform MegaCam and, with the exception of confusion-limited applications, IMAKA as well.

Even more formidable competition will appear towards the end of the decade, when LSST and WFIRST are expected to arrive on the astronomical scene. WFIRST is a $1.6B wide-field imaging IR space telescope that aims to map an area of $\sim$16,000 deg^2 at IR wavelengths; it was recently ranked as the highest priority space facility in the US Astro2010 Decadal Report (Blandford et al. 2010). Likewise, the highest priority ground-based facility identified in this study was LSST, an 8.4m wide-field optical telescope that aims to survey an area of $\sim$20,000 deg^2, imaging each part of this region roughly 1000 times over its ten-year lifetime. While LSST and WFIRST are largely motivated by the need to better understand the nature of dark energy, both facilities are expected to enable countless ancillary science programs (which partly explains their high rankings in the Astro2010 report). LSST, in particular, is seen as the heir apparent to the SDSS, although with one notable exception: as a strictly imaging telescope, it will lack the spectroscopic component that helped make SDSS the highest-impact telescope of the last decade (see, e.g., Madrid & Macchetto 2006, 2009; Chen et al. 2009).

2. SCIENTIFIC DRIVERS FOR WIDE-FIELD MULTI-OBJECT SPECTROSCOPY

As Table 1 shows, a new generation of facilities will soon be producing the vast imaging datasets that will be used to address the key scientific questions of the coming decade. However, it is also clear from Table 1 that telescopes capable of obtaining the requisite follow-up spectroscopy have not kept pace, with the exception of 4m-class facilities like LAMOST and AAT, both of which will soon (i.e., 2012) be embarking on ambitious (10,000 deg^2) Milky Way surveys aimed towards understanding the structure and evolution of the Galaxy in the GAIA era. To capitalize fully on the deep imaging that will be provided by LSST and other imaging facilities, an 8-10m-class telescope that can obtain optical spectroscopy for thousands of faint sources over a large field (i.e., $\sim$1 deg^2 or more) is needed. Moreover, any such facility should be located in an exceptional site, with excellent seeing and dark skies, to reduce background light for faint, compact targets (i.e., $z \gtrsim 1$ galaxies and stars in the Galactic halo or external galaxies).

The science case for an 8-10m-class telescope equipped with a wide-field multi-object spectrograph is universally recognized, having been thoroughly explored in a several studies during the past decade. Indeed, it is worth noting that, a decade ago, the LRP2000 report stated that "The LRPP recommends that our community quickly obtain significant participation (40%) in the construction and operation of a new, optical/infrared 8 meter class telescope. Wide-field capability (WF8m) should be given priority." Since that time, the science case for such a facility has only sharpened (e.g., Dey et al. 2005; Ellis et al. 2009; Barden et al. 2009), with the appreciation of how such a facility could enable transformational science, most notably by: (1) constraining the *dark energy equation of state* to a level of a few percent and; (2) exploring *the structure, kinematics and chemical evolution of the Milky Way* (i.e., Galactic archaeology).

These two science cases have been thoroughly explored in previous WFMOS studies so we shall not repeat them here; the interested reader is referred to the above documents for details. However, given that CFHT has historically enjoyed success as a facility that serves the diverse needs of broad communities, we point out that a 10m telescope equipped with an WFMOS-like instrument (our proposed upgrade for a Next Generation CFHT, ngCFHT; see below) would have a transformative impact in a wide range of fields including stellar structure and evolution, large-scale structure, galaxy formation and evolution, dark matter, AGN physics, and the epoch of reonization. The nearest analog in terms of potential impact across subfields would probably be the SDSS, with more than 3000 papers (covering nearly every field in astrophysics) and 100,000 citations to date (Raddick & Sazlay 2010).

As one example of how ngCFHT might fulfill its key science goals of characterizing dark energy and the stellar populations of the Milky Way and simultaneously enable exciting ancillary programs, Figure 1 shows how observations in the direction of the Virgo Cluster could be tailored to select baryonic tracers (e.g., galaxies, star clusters, PNe, etc) to probe the distribution of dark matter and the structure of the baryonic velocity ellipsoid. In $\sim$ 280 hours of observing time, ngCFHT could obtain spectra for more than 50,000 baryonic substructures in Virgo, opening a new field in astrophysics: extragalactic archaeology. Such programs would be feasible only with ngCFHT, thanks to its combination of collecting area, field coverage and multiplexing.

Finally, consider the efficiency of ngCFHT in carrying out a "legacy" spectroscopic survey of $\sim 10{,}000$ deg^2 (chosen for comparison purposes to SDSS). Covering this area to a depth of $g \approx 23.5$ (achievable in 2 hrs at $\mathcal{R} = 1500$ for S/N = 5 per Å; see Table 2) would require about 8 years (assuming 80% useable nights) and yield spectra for ∼30 million sources. No existing or planned facility could undertake a spectroscopic survey that approaches this in terms of depth, areal coverage or sample size. We nevertheless point out that, although surveys would surely be a strong component of any ngCFHT operations plan, this need not preclude PI-based observing programs.

3. PROPOSED UPGRADE: A NEXT GENERATION CFHT

The idea of replacing the 3.6m CFHT with a much larger telescope is not a new one (e.g., Richer et al. 1998; Carlberg 1999; Geyl et al. 2000; Burgarella et al. 2000). Many concepts have been considered but perhaps the most comprehensive report is that of Grundmann (1997) who carried out a study (commissioned by CFHT) to "identify the largest telescope which could reasonably be installed making use of the existing pier". The answer was a 12–15m segmented mirror alt-az telescope similar to the Keck 10m design. Despite the huge increase in collecting area, the weight of the Keck mirror and cell is only ∼10% larger than that of CFHT, and the telescope weight is similar so there is little doubt that the CFHT pier would be able to support it. Because the CFHT 3.6m primary has a very slow ($f/3.8$) focal ratio, a much larger modern telescope could be accommodated within a dome of similar size to that of CFHT (i.e., current telescopes have primaries with f/ratios ~ 1). Of course, the current dome, which has a shutter width of only 6.5m, would need to be replaced with one having a larger aperture.

In what follows, we rely heavily on the findings of the Grundmann report to propose a ∼10m replacement for CFHT. We also recommend building on existing designs and facilities to minimize cost, schedule and risk: in particular, by leveraging the designs of the Keck/TMT telescopes and copying that of WFMOS, the Gemini commissioned study of a Wide Field Spectrograph for Subaru.

3.1. *Telescope and Support*

Although the Grundmann report indicated that a telescope with an aperture in the range 12–15m could be considered, it is clear that it would be simpler, faster and cheaper to just copy Keck. This is true in terms of fitting on the pier and within an enclosure of similar size, but also because of the physical image scale and sizes that a larger primary implies for any wide field instrument (including correctors, etc).

The heart of any telescope is, of course, the primary mirror which for Keck is composed of thirty six, 1.8m hexagonal segments. Because that segment production option no longer exists (J. Nelson, private communication), the TMT and the E-ELT projects each invested considerable resources in determining what the optimum, most cost-effective, segment size should be. Both studies concluded that the optimum segment size is 1.4m or less. Consequently, we propose that the primary mirror should be made of ∼1.2m segments with a total aperture of 10m. The primary f/ratio should be $\sim f/1.6$ or faster so that the physical size of a wide-field corrector is similar or smaller than that of Subaru (8.2m, $f/2$ primary).

Ideally, the telescope would be optimized only for wide-field spectroscopy at the prime focus, thereby simplifying its design and obviating the need for other focal stations. As the Grundmann report notes, Keck is supported on an azimuth track that is comparable in diameter to the CFHT telescope pier, giving us confidence that a Keck-type design will function well on the basic CFHT foundation. Figure 2 shows Grundmann's sketch of a 10m telescope on the CFHT pier and inside an enclosure with the same dimensions (but with a larger shutter aperture) as the current CFHT dome.

The Keck II telescope, including the building and dome, cost about ≈ \$70M in 1996. Inflation might well be offset by exploiting the groundwork laid by TMT on the segmented primary mirrors, telescope structures and calotte enclosures (see below). Moreover, the very substantial pier, foundation and support building already exists, so that, according to Jerry Nelson, "the cost of the telescope and dome is liable to be between \$50-100M". This is generally consistent with the conclusions of Grundmann (who estimated a cost of roughly \$70M for a 12m CFHT) so we proceed with an estimate at the upper end of this range: \$100M. Needless to say, a detailed concept study is required to substantially improve the fidelity of this crude estimate.

3.2. *Telescope Dome*

Studies demonstrate that the most efficient and cost-effective enclosure design is a calotte-style dome, as advocated by Dynamic Structures Limited (DSL) and ultimately adopted by TMT. Maintaining the overall exterior dimensions of the enclosure would ensure minimal impact on the cultural and ecological aspects of Mauna Kea, although it may prove advantageous to utilize a reflective aluminium surface rather than the current white exterior.

3.3. *WFMOS*

Not surprisingly, the key scientific programs for an ngCFHT would be very similar to those that emerged from the Gemini Aspen process and so the instrument requirements are essentially identical to those for the Gemini WFMOS instrument.

In 2008, Gemini commissioned two in-depth conceptual design studies for WFMOS, which was to be mounted on the Subaru wide field corrector (Ellis et al. 2009; Barden et al. 2009). The basic instrument we are considering (Figure 2) borrows heavily from the Ellis et al. (2009) concept, which employs a novel fiber positioner that can be reconfigured in just ∼ 40s (an important consideration when carrying out large surveys). The baseline WFMOS design for low spectral resolution ($\mathcal{R} \approx 1500$ to 5000 for three different gratings) incorporates 2400 fibers in a hexagonal configuration that is 1.°3–1.°4 across, feeding three spectrographs; at higher resolution, spectra from 600 fibers are cross dispersed to deliver $\mathcal{R} = 20{,}000$ spectra over a broad bandpass. This design promises excellent throughput (12–40% including atmosphere) through use of the latest high efficiency fibers, dedicated VPH gratings and high-QE detectors.

The WFMOS design was partly constrained by the size of the Subaru corrector (1.°5 in diameter, but with some vignetting) and available space for the spectrographs.

More fibers and spectrographs could be incorporated in a version for CFHT. According to the Ellis et al. (2009) report, adding another 800 fibers would increase the cost by only \$3.7M (\$4.4M with contingency). Hence we baseline an instrument with 3200 fibres and four spectrographs (which would allow 800 targets to be observed in high-resolution mode). More details on the spectroscopic options are given in Table 2.

The total cost of WFMOS was estimated to be \$68.5M including 20% contingency. However, this included \$8M for modifications to Subaru hardware and software — items that would not be required for a purpose-built telescope. Subtracting this, but adding in the increased cost of additional fibers, brings the estimate to \$64.9M.

3.4. *Schedule and Downtime*

In 1997, DSL estimated that dismantling the CFHT dome and telescope would take 8.5 months and that a shutdown time of 3.5 to 4 years would be required to upgrade the 3.6m telescope to a larger facility. Grundmann estimated that the entire project would take seven years, based largely on the experience with Gemini and Keck I, including a $\sim$4 year shutdown period. Thus, it seems reasonable to assume that design and manufacturing efforts could begin early in the coming decade, with civil works on site (including telescope/enclosure erection and integration) commencing around 2016. The goal would then be to achieve first light with ngCFHT by 2020. Such an aggressive timeline is essential for two reasons: (1) there is guaranteed to be fierce, and growing, competition in the study of dark energy and Galactic archaeology in the coming years; and (2) first light in 2020 would ensure maximum synergy with LSST, WFIRST, GAIA, TMT and E-ELT, all of which are hoped to be in operation around this time, as well as with more mature facilities like ALMA and JWST.

4. EXPANDING THE PARTNERSHIP?

We again stress that a detailed concept study is needed to fully explore the many design options and refine the above cost estimates. However, at this early stage we are able to loosely constrain the cost of the ngCFHT project to be in the neighborhood of \$165M (not including operational costs). Could the resources be found to allow such an upgrade to proceed?

Since it may not be possible for the current CFHT partners to raise all of the required funds, an obvious alternative would to bring new partners into the project. There are many potential partners given the widespread interest in wide-field spectroscopic science with a 10m-class telescope. These include: (1) Japan, who are actively looking into the development of a WFMOS-like capability for Subaru; (2) China and India, prospective TMT partners who have each expressed interest in gaining access to a 8-10m-class telescope; (3) Australia, who have considerable community interest and expertise in wide-field optical spectroscopy; and (4) large US institutions such as, Princeton, Harvard or CalTech (who already have an advanced WFMOS design). Discussions with these and other prospective partners could begin immediately, to explore the terms for a possible expansion of the CFHT partnership.

As discussed in §1, the success CFHT has enjoyed over the last three decades is due, first and foremost, to the scientific and technical vision of its partners. There are, however, additional factors that have played important roles: an effective governance model, the complementary strengths of the different communities, and the balanced role of the major partners. It would be highly desirable to strive towards a comparable balance in any expanded partnership. If we consider an expansion that adds 1–2 new (and equal) partners, then the contributions of Canada and France (for an assumed ngCFHT cost of \$165M) would be in the range $\sim$\$25-\$50M, depending on the valuation of the existing site and infrastructure.

5. COMMUNITY IMPACT AND ACCESS TO NEW FACILITIES

The ngCFHT we envision here offers a single, extremely powerful instrument. At first glance, this reduction in instrument complement may appear to be a concern for the present users of CFHT. It is, however, a natural progression in the evolution of the telescope, which, 15 years ago, featured multiple top-ends, 6-8 science instruments, and an active visitor instrument program. As discussed in §1.2, there have been only three facility instruments available for the last five years, yet their unique capabilities (and the shift toward larger programs and surveys) have allowed CFHT users to remain at the forefront of astronomical research. This will undoubtedly be true of a wide-field 10m telescope equipped with WFMOS, as it would enable countless scientific programs beyond dark energy and Galactic archaeology. Nor does our proposed upgrade preclude the introduction of new, cost-effective capabilities such as feeding a higher resolution ($\mathcal{R} \gtrsim 50{,}000$) spectrograph with one of the WFMOS fibers.

But, above all, ngCFHT would be an extraordinary research tool that would likely be sought after by the users of other facilities. Members of the partnership could re-evaluate the level of their participation in older 8m-class telescopes (such as Gemini and VLT), or decide whether to use ngCFHT as a means of securing access to other, newer facilities having capabilities that meet the needs of their respective communities.

CFHT has had a profound impact in astronomy, having produced cutting edge science for three decades. Its member communities are recognized as world leaders precisely because they showed the vision to modify the telescope's capabilities in response to changes in the scientific and technological landscape. There is now a tremendous opportunity to transform CFHT once again — into the world's preeminent spectroscopic telescope at a time when demand for such a facility has never been greater.

TABLE 1
Wide Field Capabilities of Post-2010 Astronomical Facilities

Inst.	Tele.	D_{M1} (m)	Status	λ	Available	Imaging	FOV (deg^2)	$A\Omega$ (m^2 deg^2)	g_{lim}[◇] (mag)	N_{spec}	$A\Omega N_{spec}$ (m^2 deg^2)
					Imaging						
MegaCam	CFHT	3.6	Existing	Opt.	2006	Y	1.0	10.2	···	···	···
PS1	PS1	1.8	Existing	Opt.	2009	Y	7.3	18.6	···	···	···
VISTA	VISTA	4.0	Existing	IR	2010	Y	0.6	7.5	···	···	···
Skymapper	Skymapper	1.35	Planned	Optical	2011	Y	5.7	8.2	···	···	···
HSC	Subaru	8.2	Planned	Opt.	2012	Y	1.7	90	···	···	···
ODI	WIYN	3.5	Planned	Opt.	2012	Y	1.0	9.6	···	···	···
DEC	Blanco	4.0	Planned	Opt.	2012	Y	3.0	38	···	···	···
PS2	PS2	2×1.8	Planned	Opt.	2012	Y	7.3	37	···	···	···
IMAKA	CFHT	3.6	Proposed	Opt.	2016	Y	0.5	5.1	···	···	···
LSST[†]	LSST	8.4	Proposed	Opt.	2019	Y	6.7	370	···	···	···
							(20,000)	(1.1×10^6)			
WFIRST[†⊕]	WFIRST	1.5	Proposed	IR	2020	Y	0.5	0.9	···	···	
							(16,000)	(2.8×10^4)			
					Spectroscopy						
DEIMOS	Keck	10	Existing	Opt.	2002	Y	0.02	1.7	···	150	2.6×10^2
IMACS	Magellan	6.5	Existing	Opt.	2008	Y	0.16	5.3	···	300	1.6×10^3
Hectospec	MMT	6.5	Existing	Opt.	2004	N	0.8	···	···	300	8.0×10^3
FMOS	Subaru	8.2	Existing	IR	2010	N	0.5	···	···	400	1.1×10^4
LAMOST	LAMOST	4	Planned	Opt.	2012	N	20	···	19.3[⋆]	4000	9.9×10^5
											(5.0×10^8)
HERMES	AAT	3.9	Planned	Opt.	2012	N	3.1	···	14.3	400	1.5×10^4
											(4.8×10^7)
GYES	CFHT	3.6	Proposed	Opt.	2016	N	0.6	···	16.3	500	3.3×10^3
											(5.1×10^7)
WFMOS	ngCFHT	10	Proposed	Opt.	2020	N	1.5	···	21.8,23.1	3200	3.8×10^5
											(2.5×10^9)

[†]For LSST and WFIRST – which are primarily survey instruments – we give both the FOV and étendue ($A\Omega$) *per pointing* and, in the subsequent row, the respective values at the end of the surveys.

[◇]Approximate limiting point-source magnitude for planned or proposed spectroscopic surveys. GYES ($\mathcal{R} = 20,000$) has a target signal-to-noise ratio of S/N ~ 50 at $V = 16$ but will extend to $V \approx 18$ at lower S/N; it aims to cover an area of 10,000 deg^2. HERMES, which will also cover an area of 10,000 deg^2, aims for completeness brighter than $V = 14$ (at $\mathcal{R} = 30,000$), but can of course be used to observe stars several magnitudes fainter than this. The two values of g_{lim} for WFMOS give the limiting point-source magnitudes for 1-hr exposures at $\mathcal{R} = 20,000$ and $1,500$ (S/N = 5 for 1 Å $pixel^{-1}$; see Table 2). $A\Omega N_{spec}$ for WFMOS is baselined to a survey of 10,000 deg^2 for comparison to the LAMOST, HERMES and GYES surveys (as well as SDSS).

[⋆]Quoted depth and $A\Omega N_{spec}$ refer to the wide (10,000 deg^2) Galactic survey ($\mathcal{R} = 5,000$); a planned 3,000 deg^2 "deep" survey would reach $g_{lim} \approx 20.0$.

[⊕]Some design options being considered for WFIRST include spectroscopy for ~10% of the galaxy sample, or $\sim 10^8$ redshifts.

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TABLE 2
WFMOS SPECIFICATIONS AND PERFORMANCE‡

$\mathcal{R}$	Wavelength Range (Å)	$N_{\rm spec}$	$g_{\rm lim}$ (S/N = 5 per Å in 1hr) (mag)	$g_{\rm lim}$ (S/N = 20 per Å in 1hr) (mag)
1500	4200-6700	3200	23.1	21.2
3500	6300-9700	3200	23.0	21.2
5000	4800-5500	3200	22.8	21.0
	8150-8850			
20000	4800-6800	800	21.4	19.7

‡Science requirements and WFMOS capabilities for the Dark Energy and Galactic Archaeology surveys from Ellis et al.(2009).

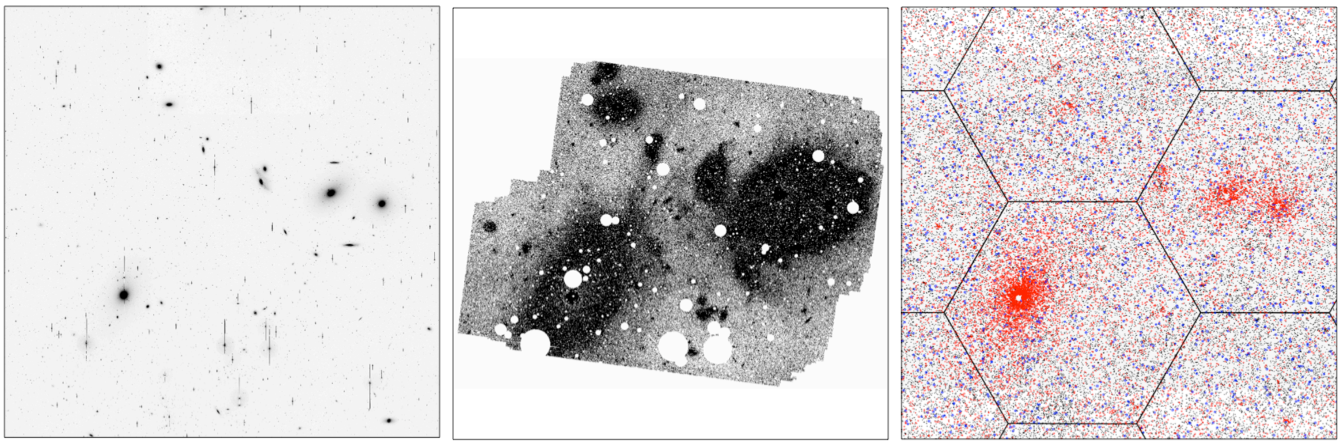

FIG. 1.— One demonstration of the power and versatility of our proposed ngCFHT — a facility that could carry out simultaneous studies of the Milky Way halo, nearby galaxies and clusters, large-scale structure, distant galaxies, and dark energy. **(Left)** An image showing a $1.^{\circ}8 \times 1.^{\circ}8$ region ($\approx$ 500 kpc $\times$ 500 kpc) centered on the core of the Virgo Cluster (D $\approx$ 16.5 Mpc) taken from the *Next Generation Virgo Cluster Survey*, a large program now underway at CFHT. The linear intensity stretch highlights the small number of bright, early-type galaxies that populate the cluster core, as well as bright (and often saturated) stars belonging to the Milky Way disk. **(Middle)** A deep view within this same field from Mihos et al. (2005). A logarithmic stretch is used to show the diffuse light and the extended halos surrounding most galaxies: the fossil record of hierarchical galaxy formation. The faintest features visible in this image have a surface brightness of $\mu_g \sim 28.8$ mag arcsec^2. **(Right)** The distribution of bright ($g \leq 20.5$) Galactic halo star, Virgo globular star clusters ($g \leq 23.5$), and background galaxies ($g \leq 23.5$) identified by the *Next Generation Virgo Cluster Survey* (blue, red and black symbols, respectively). The hexagons show a WFMOS field of view similar to that proposed by Ellis et al. (2009). Such an instrument operating on a 10m-class ngCFHT would open a new era in astrophysics. In a single 50-night program ($\sim$280 hours of observing time), the ngCFHT could measure radial velocities good to $\pm$20 km s^{-1} ($\mathcal{R} \sim 1500$) for $\sim$ 1500 galaxies, 40,000 star clusters, and 10,000 planetary nebulae in the Virgo Cluster (an area of 100 deg^2), measuring the distribution of dark matter and the shape of the velocity ellipsoid for baryonic substructures. It would also obtain intermediate-resolution (S/N $\geq$ 20) spectroscopy for 20,000 Galactic halo stars, and $\sim$ 240,000 background galaxies.

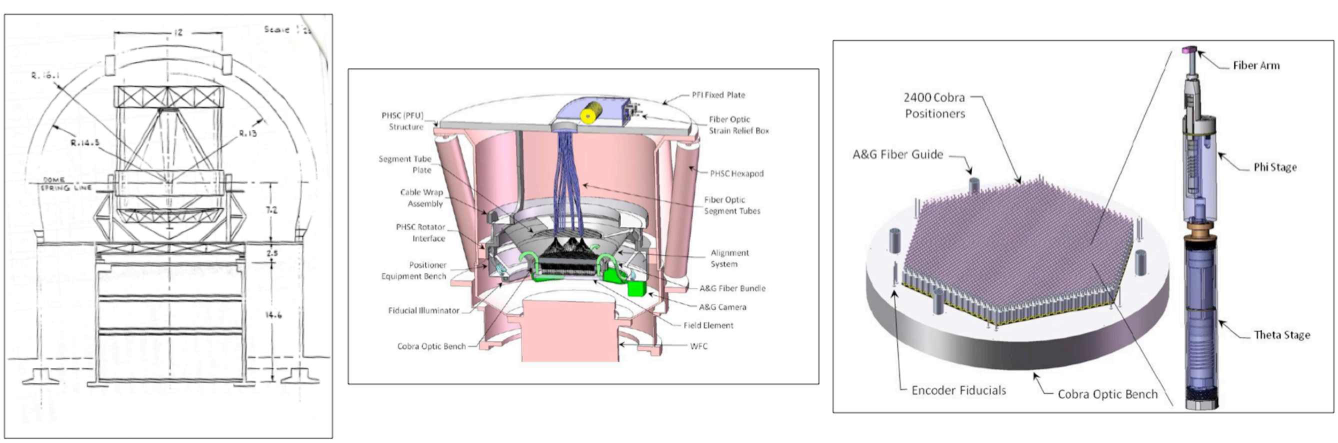

FIG. 2.— **(Left)** Cross sectional view of the CFHT with a 10m telescope mounted on the existing pier. Figure from Grundmann (1997). **(Middle)** Schematic of the WFMOS Prime Focus Instrument (consisting of the acquisition and guide cameras, the field element, the positioner subsystem and other telescope-mounted components) taken from Ellis et al. (2009). **(Right)** The Cobra positioner system from Ellis et al. (2009), which covers the WFMOS focal plane with 2400 positioners to fill a hexagonal field. A magnified view of a single positioner is shown at the right.