Scientific Windows of Opportunity for the Canada-France-Hawaii Telescope

Abstract: *I briefly review the contributors to the scientific success of an astronomical facility. I then attempt to identify the scientific questions that will be of paramount importance in the next 10 years and which can be addressed by telescopes such as the CFHT and discuss the generic capabilities that will be required for their solution. High spatial resolution and a versatile capability in the infrared waveband emerge as common requirements for tackling these questions. CFHT is ideally suited to provide these capabilities.*

The CFHT in the 1990's

One can identify five main contributors to the scientific success of a telescope.

- The quality of the site at which the telescope is located. With careful management this may be preserved for indefinite periods of time and CFHT is fortunate to occupy what many consider to be the best location on the best astronomical site.
- The light collecting area (i.e. the aperture of the primary mirror) and other relatively immutable features of the telescope. These can only be altered at often prohibitive cost.
- The instrumentation, in which I include not only the cameras and spectrographs and their detectors but also the systems such as the acquisition and guiding controls, the computer control software and so on.
- The astronomers themselves who must devise and execute the most efficient observational programs sometimes under difficult conditions.
- The Time Assignment committee who have the difficult task of apportioning the limited amount of telescope time between the many competing proposals that together could account for many times the available time.

The last forty years have seen dramatic advances in the power of large telescopes. Some of this has been due to the development of superb ground-based sites such as Mauna Kea, but by far the largest advance has been in the realm of instrumentation. Most dramatic has been the enormous gain in the quantum efficiency of detectors - modern solid-state devices such as CCDs are close to being "perfect" detectors. The gains in detector quantum efficiency can not be carried much further and this realization has formed part of the motivation for the design and construction of a new generation of telescopes with primary mirrors that are substantially larger than the 3.6-m of CFHT. The first of these, the Caltech-university of California "Keck I" 10-m telescope is nearing routine operation on Mauna Kea and at least eight more 8-m class telescopes are due to be completed by the year 2000. The looming presence of these behemoths is doing much to focus our attention on how best to use CFHT into the next century.

However, there are still very large potential gains to be made in instrumentation. Particular emphasis is being placed on multiplexing - i.e. on increasing the power of the telescope by increasing the number of available detecting elements and by increasing the efficiency with which those elements are used to collect data. One very obvious approach is to construct mosaics of panoramic detectors such as CCDs in the focal plane. For many survey-type observations this leads to a direct increase in the area observed in a given amount of time and/or a reduction in the amount of time required to survey a fixed area to a given depth. Multi-object spectrographs are being constructed with progressively wider fields of view to take advantage of large format CCDs, dramatically increasing the number of objects that can be observed simultaneously.

In spectroscopic observations there are trade-offs between "sky" and "objects" in a spectrograph. A conventional long-slit dispersing spectrograph takes light from a single object and much unwanted sky. A multi-slit spectrograph employs a focal-plane mask to position shorter slits over many objects simultaneously thereby reducing the amount of "wasted" sky data while fibre-fed spectrographs provide an even more flexible choice of objects to be observed. More subtle multiplexing is achieved in the relatively new field of instrumentation of so-called "integral-field" spectrographs in which optical fibres or other optical systems such as an array of lenslets are used to examine the light from a contiguous two-dimensional area of sky simultaneously without the constraints of a one-dimensional spectrographic slit. Finally, Fabry-Perot type cavity-spectrographs view an enormous field but obtain only one spectral element at a time.

Innovative designs for instrumentation that maximize this multiplexing effect can go a long way to reducing or even eliminating the competitive advantage that larger telescopes gain by virtue of their larger collecting areas. At a meeting such as this, it is the task of the CFHT User Community and the Scientific Advisory Committee to ensure that the instrumentation available on the CFHT and the time allocation philosophies of the TACs enable the most significant science to be done with the telescope.

Astronomical Directions

Looking at the subject in the broadest possible terms, I believe that it is possible to discern a subtle shift in emphasis in astronomical research: For several centuries astronomers have been concerned with first discovering and describing the different structures found in the Universe and then seeking to understand how the objects work in terms of astrophysics. As examples one can readily think of the discovery of the overall distribution of matter in terms of form of the Milky Way Galaxy and the external galaxies (1850-1950), or of the stupendous achievement of understanding the interior workings of stars in the middle years of this century, or of the extraordinary data returned by the robotics explorers of the outer Solar System.

Of course, many interesting questions remain: we do not yet know how common planetary systems are in the Galaxy and there are still many uncertainties in aspects of stellar astrophysics. The distribution of matter on the largest scales in the Universe is also poorly described. Nevertheless, I would argue that there is a growing awareness of the need to understand the *origins* of these structures. Perhaps this stems in part form the success of the Big Bang cosmology in describing a beginning for the Universe.

Thus, as we approach the close of the 20th century, it is likely that the major scientific questions will enter on the origin of planetary systems, the formation of stars, the formation of galaxies and, most profoundly, the origin of the Universe as a whole. As I will argue below, users of the CFHT are fortunate that the telescope is ideally suited to making major contributions in these areas. I list here some of the key questions that optical-IR telescopes such as CFHT can profitably address and the generic capabilities that are required to do so.

1. The Origin of Stars and Planetary Systems

We know rather a lot about the properties of stars and are observing many complex processes in star formation regions. To a certain degree we perhaps know too much — we have many more questions than answers. Our poor understanding of star-formation at present is the greatest missing link in our understanding of stellar evolution which is surely one of the great achievements of 20th century science, while a deeper insight into planetary formation would profoundly affect our awareness of our place in the Universe.

Questions

- What causes the mass limits of stellar objects $(100M_\odot < M < 0.08\ M_\odot)$ and do lower mass objects, i.e. brown dwarf, exist in significant numbers. What physical processes determine the initial mass function in different locations and at different epochs?
- What supports the dense cores of molecular clouds and what triggers their collapse?
- How is angular momentum lost during proto-stellar collapse?
- How do accretion disks work and how are the jets of outflowing material collimated? What are the kinematics and compositions of circumstellar disks?
- What is the role of magnetic fields?
- How common is the formation of planetary systems in circumstellar disks?

Science requirements

Observational insight into many of the above questions requires some broad generic capabilities:

- Most of the interesting physical scales are *small, so high spatial resolution* is very important. For instance, a scale of 10 A.U., typical of planetary systems and protostellar disks, placed at the distance of the nearest star formation region subtends only 0.1 arcsec.
- We are usually dealing with *cool* objects, either collapsing protostars or material warmed to modest temperatures by nearby luminous objects. Furthermore, there is frequently very high *extinction* caused by dust along the line of sight to the cores of the molecular clouds where some of the most interesting phenomena are occurring. These both make observations in the *infrared waveband* essential.
- The physical processes are expected to be *complex and arisotropic.* This will put a premium on *integral field spectroscopy* where information is obtained from all points in a restricted field of view without the constraints imposed by use of a one-dimensional spectrographic slit.
- The velocities of material in star-forming systems will range down to *planetary velocities* of order 10 km/s, requiring *spectral resolutions R ~30,000.* However the use of physical line diagnostics requires only a lower resolution (R ~ 1000) so as to isolate individual components of the molecular rotational levels within each vibrational levels.
- The importance of distinguishing between intrinsic emission and *scattering* and the probable role of *magnetic fields* in star-formation makes *polarization data* important.
- Some of the most interesting objects are extremely *bright*, so that a large amount of detailed data can be obtained. Furthermore, working from the ground in the *thermal IR* region $\lambda > 2\ \mu m$, is a practical proposition.

2. The Formation and Evolution of Galaxies and Large Scale Structure

The observational study of the formation and evolution of galaxies is still in its infancy. We know rather little by direct observation, and are presently seeking to sketch out the broad basics. Again, we may identify the origin and evolution of structure in the Universe on galactic scales and above as a major missing link in the otherwise outstandingly successful scientific theory of the Universe that is contained in the Big Bang model for the Universe.

Questions

- When did the earliest stars in the Universe form and significant chemical enrichment begin?
- When were the dark matter haloes of galaxies of different masses assembled and when , and where, did the stars that we see today in them form?
- What is the relationship between the mass distribution and the light distribution in the Universe, i.e. the general "biassing" question?
- What has been the evolution of the largest bound structures in the Universe, the rich clusters of galaxies?
- What physical processes have controlled the evolution of galaxies on different mass scales, both through feedback loops within galaxies and through interactions of galaxies with their environments?
- What is the form of the AGN luminosity function through time and what is the relationship between this and the formation and evolution of galaxies?
- Can we understand extragalactic systems well enough to use them as probes of the geometry and evolution of the Universe as a whole?

Science Requirements

- Distant objects are small, so *angular resolution* is again at a premium. A typical galactic scale of $1 h_{50}^{-1}$ kpc subtends 0.1 arcsec at cosmological redshifts, $z{\sim}1$.
- The effect of the redshift is to shift the rest-frame optical waveband into the near infrared waveband. Thus, the familiar spectral diagnostics are to be found in this waveband. Of more importance, observations in the near-infrared offer the best handle on the presence of older stellar populations in galaxies. At very high redshifts, objects such as quasars at $z>7$ may be completely

invisible at optical wavelengths because of intervening absorption at rest wavelengths $\lambda < 1216$ Å. A versatile capability is the *near-infrared* out to the onset of the thermal IR at 2 μm is thus extremely important.

- We are frequently looking for evolutionary changes in a very large population of objects (literally the contents of the Universe in some cases) and thus the most productive studies are usually statistical in nature. This sets a high premium on efficient *multiplexing* of survey-type observations so that large numbers of objects can be observed.
- Distant sources seen at large look-back times are necessarily faint, so the amount of information that can be gathered, even with very efficient instrumentation, is quite limited. Furthermore, working effectively at wavelengths longer than 2 μm has been shown to be very difficult from ground-based 4-m class telescopes.
- Typical velocities for structures within galaxies are 10^2 km s^{-1} requiring resolutions of up to 3000. Those in clusters of galaxies are ten times larger.
- Many of the most interesting spectral lines for abundance studies in stars and gas clouds are at ultraviolet wavelengths.

3. Dark Matter

I suspect that the growing awareness over the last 15 years of the importance of Dark Matter in the Universe will prove, in retrospect, to have been one of the great revolutions in astronomy and so I thought it merited a section of its own. In discussing the future of CFHT, this may seem paradoxical, since the telescope can by definition study only luminous matter! Such a point of view is illusory of course and CFHT has already made major contributions to this field.

Specific questions that we would like to address might be:

- What can we learn about the distribution of Dark Matter on the scales of galaxies and clusters of galaxies?
- What can we learn about the origin of the density fluctuations that produce structure in the Universe, and assuming they are primordial, what do they tell us about the physics of the very early Universe?

The Science Requirements are very similar to those of (2) above since the required observations are usually either of the internal structure of galaxies or, most revealing, of the gravitational lensing effects of intervening mass on galaxies and quasars.

Several common threads emerge from the previous discussion: The two most important are the need for the *highest possible spatial resolution* and the need for a strong *capability at infrared wavelengths,* particularly in the 1-2 μm waveband. We are fortunate that at CFHT we have a fine telescope on an outstanding site that should guarantee us competitive image quality in the future. Furthermore, the Corporation appears determined to stay abreast of developments in Adaptive Optics that will enable maximal exploitation to be made of these natural advantages.

The CFHT is also at last making an, in my view belated, effort to acquire state of the art detectors in the near-IR that should in short order catch up much of the lost ground in this vital area and a number of imaginative proposals for near-infrared instrumentation have been discussed at this meeting.

Summary: *The user communities of the CFHT are well-placed to make very productive use of the telescope in to the next century and should be able to make substantial progress towards answering some of the most important and fundamental questions in astronomy.*

Acknowledgements: *In preparing for this presentation, I benefited greatly from the perspectives of C. Pritchet, J. Bergeron and F. Boulanger. I am also grateful to the organizers for making this meeting so enjoyable and, I hope, ultimately successful in directing the future of the CFHT.*

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Note: This talk has been presented at the CFHT Users' Meeting, held in Victoria (Canada) in May 1992.

LATEST NEWS ON INSTRUMENTATION

Status of the Coudé F/4 Spectrograph Project

A great deal of progress has been accomplished on the Coudé f/4 high resolution spectrograph since the publication of the last Information Bulletin. The support pedestals, mirrors supports, filter wheel unit, grating and grism tables, as well as the motorized mosaic cell were delivered to CFHT from DAO in May, 1992. The CFHT Electronics group carried out the [extensive] wiring of these units in Waimea prior to their installation at the summit in August-September, 1992. The control system software was contracted to William Rambold, who spent all of September, 1992, installing and verifying the software, and training CFHT staff on its detailed workings. The Software Group has created a Pegasus session that provides control over all of the spectrograph functions as well as the detectors used for data-taking.

The mirrors and lenses were installed at the summit in September and first light on stars was achieved on the night of September 17-18, 1992, thanks to much hard work, long hours, and admirable dedication of the many members of "Team Coudé". Since the grisms had not been received, order sorting filters were used for these tests as well as additional tests on the nights of October 3-4 and 4-5, 1992.

Following these nights, the mirrors and the mosaic were removed, the pedestals supporting them were permanently bolted to the floor, and the optics were reinstalled in anticipation of additional software development and optical alignment.

First spectra with the Coudé F/4 spectrograph were taken during the evening of September 17, 1992, using the Red optics, just before the first stellar spectra. Additional observations were made on October 3-4 and 4-5, using the UV as well as the Red optics, and included initial tests with the new image slicers.