ADAPTIVE OPTICS FOR ASTRONOMY: A STRONG CANADIAN ASSET

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ABSTRACT

Thanks to a rich legacy of more than 20 years, Canada is established as a strong leader in the field of adaptive optics. Adaptive optics is absolutely critical for current and future ground based telescopes, and the key to maintaining Canada's leadership in the coming decade and beyond will be a strong synergy between HIA, Canadian universities and Canadian industry.

1. PAST ACCOMPLISHMENTS AND CURRENT STATUS

1.1. *AO instrumentation for current telescopes*

Canada's leadership in AO started well before the beginning of the last decade, with the delivery to CFHT of HRCAM, a "simple" tip-tilt corrector in 1988 that produced the highest-resolution images before HST, and PUEO (in collaboration with France, in 1995) – the most user-friendly and scientifically productive AO system of its generation. That early investment in AO paid great dividends with the successful delivery of HIA-made Altair to Gemini North in 2002. Altair, which initially worked in natural guide star (NGS) mode, achieved an unprecedented level of automation ("one button operation") and of integration with the telescope, leading to a scientific productive instrument, very competitive with similar instruments being deployed at 8-meter class telescopes in the same time frame. In 2005, Gemini North was equipped with a laser guide star (LGS). This vastly increased Altair's sky coverage, and, especially with the coupling in 2006 with the integral field spectrograph NIFS (a desirable combination also favored at VLT and Keck), dramatically increased the scientific reach of AO, especially towards extra-galactic astronomy.

By achieving on current generation of 8–10 meter telescopes spatial resolutions in the near-infrared comparable to those of HST at visible wavelengths, and by making these high spatial resolutions available over a large fraction of the sky with LGSs, AO has opened up a tremendous discovery space. The last decade has seen a major surge of scientific publications based on AO-assisted observations (now about 100 per year). Two prime examples are the direct imaging of the first extrasolar planetary system, and the measurement of black hole masses in our own and nearby galaxies from kinematics of stars and gas (see figure 1).

While first generation AO systems were becoming a core capability of virtually all modern observatories, AO scientists and astronomers were developing new AO concepts and architecture for the second-generation AO systems. Much effort was put towards overcoming the limited corrected field of view (FOV) in the first generation AO systems. In the late 90s, Gemini boldly embraced the emerging concept of multi-conjugate AO (MCAO), which promises to approximatively triple the corrected field, while maintaining a very uniform PSF, by using several deformable mirrors and several laser guide stars. The system is now nearing completion with first light scheduled in 2010 and science operations hopefully in 2011.

Pushing for on-axis performance led to AO-based high contrast imagers, which associate a very high order AO system with a high performance coronograph and novel observation techniques to improve the contrast of the science images by up to a factor 100. Unprecedented discovery space was thus opened up, especially regarding the detection and imaging of extra-solar planets. The Gemini Planet Imager (GPI) project, started in 2003, is currently scheduled for first light in 2011. While the GPI team was initially centred in California, Canada (HIA and UdM) was invited to join this $25+M project. Our involvement has gradually increased to the point where we are now the largest partner.

Pushing the AO corrected field to several arc minutes is only possible by not correcting all the atmospheric turbulence. Instead, only the (usually strong) ground layer is corrected, leading to "improved-seeing" as opposed to diffraction-limited images. This concept called GLAO has been demonstrated at SOAR and MMT, and is being deployed at VLT and LBT. In 2003-2004, HIA led a successful feasibility study to retrofit an adaptive secondary mirror to Gemini North in order to enable GLAO-enhanced observing, including the design (courtesy of INO) of a wide-field camera. The study concluded that deploying such a facility was feasible at a reasonable cost. It would improve the delivered FWHM to all the Gemini instruments by about 0.1 arcsec in good to typical conditions and in turn would increase the overall efficiency of Gemini by roughly 50%. These results were endorsed by a one year long site survey to fully characterize the atmospheric turbulence at Mauna Kea. More recently, Canada supported the feasibility study of 'Imaka, an ambitious concept of a GLAO-assisted 1 degree FOV imager for CFHT. HIA supported the performance evaluation, which found that, thanks to the use of orthogonal transfer CCDs enabling local tip-tilt correction, the image quality at CFHT could be reduced to about 0.3" FWHM at R-band over the entire field ('Imaka Team 2009). HIA, ComDev and INO each also contributed an optical design to the study. It is worth noting that another study has found that ventilating the

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CFHT dome to minimize local turbulence and upgrading the optics of the telescope could also achieve comparable performance without AO (Racine 2009).

1.2. *AO instrumentation for the TMT*

During the last decade, Canada assumed a strong leadership role in the global effort to build a 20+ meter telescope, which culminated in 2003 with the publication of the VLOT book and Canada joining the TMT partnership. AO was certainly a major component in this achievement. HIA immediately became very involved in the TMT AO program, and was awarded a workpackage for the conceptual design of NFIRAOS, a first light LGS MCAO system which sets the very ambitious top level requirement to achieve a Strehl ratio of 60% at H, with a sky coverage of 50% at the Galactic Pole. This effort continues and is currently in preliminary design phase.

In 2005–2006, HIA led the feasibility of the Multi-Object AO (MOAO) module of the TMT IRMOS instrument, which proposed to simultaneously deploy 20+ IfUs in a several arcminute FOV, with AO correction at each IfU. Meanwhile, UdM supported the feasibility study of PFI, a high-contrast imaging instrument that could detect extra-solar planets about three times closer to their parent stars than GPI could, thus opening up a vast new discovery space. While both IRMOS and PFI were very highly ranked scientifically, the technical risks identified in the feasibility studies were deemed too high to be considered as first light instruments, so TMT discontinued work on them.

1.3. *AO R&D and support activities*

By the late 90's, it was widely recognized that expanding the capabilities of the first generation AO systems could significantly increase their scientific productivity. To that end, HIA partnered with Gemini in their MCAO project until PDR in 2001 and developed powerful analytical modeling tools such as PAOLA (Jolissaint et al. 2006) to evaluate the performance of advanced AO systems, as well as integrated modeling tools to evaluate the interaction between instruments and the other telescope systems. However, it became clear that many technical challenges could only be tackled through well-controlled laboratory and field experiments. While earlier, one-off AO experiments (Burley 1997; Ivanescu et al. 2003) were valuable in spreading Canadian AO expertise beyond HIA, Canada's experimental AO R&D capabilities entered a new era with the founding of the UVic AO Laboratory in 2001. The UVicAOLab was initially funded by a joint UVic/HIA application to the CFI/BCKDF program. It has been a tremendous success and continues to undertake leading-edge AO research; most notably the breakthrough development of a laboratory-based laser guide star simulator for extremely large telescopes (Lardiere et al. 2008). The UVicAOLab is the main AO support laboratory for TMT (particularly NFIRAOS) and is also currently performing complex AO experiments for ESO. As of the end of 2009, the UVicAOLab had received more than $4M from CFI, NSERC and provincial agencies for its infrastructure and base staffing, in addition to contributions towards specific workpackages from TMT via ACURA, HIA and ESO. That surely represents a very significant level of funding, and therefore an important asset for Canada.

AO-related field experiments have included the UBC group, who used the 6-meter Large Zenith Telescope (LZT) to obtain profiles of the sodium layer with unprecedented temporal and vertical resolution (Pfrommer et al. 2009). Those critical data were used at the UVicAOLab to validate the NFIRAOS WFS algorithms (Conan et al. 2009), and have now been shared with many other AO projects. In collaboration with UVic, HIA also built VOLT, an open-loop AO testbench for the DAO 1.2 meter telescope, and became the first group to demonstrate open-loop AO on the sky (Andersen et al. 2008), effectively retiring one of the main risks highlighted in the TMT IRMOS feasibility study.

Other AO related developments in Canada during the last decade include the development of post-AO instrumentation and observing techniques at UdM (Marois et al. 2006), as well as liquid deformable mirrors at UL (Borra et al. 2008), the latter receiving $600K from CFI for a new AO lab directed towards vision science AO and optical testing.

1.4. *Lessons learned*

Despite the resounding successes of the last decade, not everything went smoothly: virtually all major AO projects took longer and cost more than expected owing to the sheer complexity of these systems. Once on the telescope, they systematically underperformed, owing to system level problems. In the case of Altair, the latter included defects in the telescope optics and support instruments, vibrations induced by other telescope systems, and plain misunderstanding of the structure of the turbulence to be corrected. The critical importance of rigorous systems engineering was probably the most important lesson learned, along with the necessity to acknowledge technical risk by allowing budget and schedule contingencies. In the case of Gemini South MCAO, these problems were further aggravated by i) adopting the ill-conceived strategy to contract out critical sub-systems to different vendors (thereby magnifying systems engineering problems) and by ii) deciding to carry out the integration of the instrument in house at Gemini, which conflicted with the operational priorities of the staff. These resulted in a delay of several years, and the system is still being integrated nine years after its PDR in 2001.

However, these painful lessons from the past are now being scrupulously applied to new developments. For example, TMT has fast-tracked the development of NFIRAOS, ahead of the other science instruments, to be in sync with the development of the telescope itself; strict modern systems engineering practices are used to insure optimal integration; cost and schedule estimation are given paramount importance project-wide, and are subject to multiple external reviews; and the characterization of the atmospheric turbulence during the TMT site survey has reached an unprecedented level of detail.

2. FUTURE OUTLOOK

In the next two years, both MCAO and GPI should begin science operations at Gemini South. With GPI, Canadian astronomers will have access to capabilities (final contrast up to ∼17.5 magnitudes at $0''.7$), which are competitive with those of SPHERE, which will be deployed at VLT. The capabilities of MCAO (stable high Strehl PSF over a 85" FOV), which were brilliantly demonstrated in 2008 by the European experiment MAD, will be unique, since no other 8-meter class telescope is planning to develop such a facility. Beyond MCAO and GPI though, the future of the Gemini instrumentation program is unclear, owing to financial pressures and to uncertainties related to the Gemini partnership. One of Gemini's priorities should be to improve the current shortcomings of Altair, i.e. the reduced performance caused by vibrations and the limited sky coverage in LGS mode. As for 'Imaka and Gemini GLAO, their fate is still being debated at scientific, political and financial levels. However, if one of those projects goes ahead, Canada will be in strong position to lead it owing to our past involvement in the feasibility studies and to our intricate knowledge of those telescopes.

If the TMT construction money is granted, we expect that the main Canadian AO project of the coming decade will be NFIRAOS, with first light scheduled for 2018. The final design, build and commissioning phases are planned to be led by HIA, with expected involvement of Canadian companies at the sub-system level and continuous experimental support from Canadian universities. Enabling the client instruments to perform high-precision quantitative astronomy (astrometry and photometry) will also be critical to the scientific success of NFIRAOS. That will require close collaboration between astronomers, instrument builders and mathematicians, to develop rigorous error budgets and key data processing techniques such as PSF reconstruction through close interaction with the instrument design team.

While working on NFIRAOS, it is important to look further ahead, towards the second generation of TMT instruments. The current global emphasis on large corrected fields and high contrast seem to favor instruments such as IRMOS-MOAO and PFI, but it is worth noting that improving the wavelength coverage of AO, either towards the visible (almost unimaginable on TMT, but potentially possible on smaller telescopes) or towards the mid-IR (where TMT, owing to its higher angular resolution, could complement JWST), could open very interesting scientific opportunities. The actual design of these instruments will not start for several years, with first light probably after 2020. However, in order to overcome the associated theoretical and experimental challenges, R&D activities must be carried out now. Canada is in excellent position to do that.

The UVicAOLab has just obtained a major CFI grant to build Raven, an MOAO pathfinder that is to be deployed at the 8-meter Subaru telescope and will be coupled to the IRCS spectrograph. Unlike traditional demonstrators, the aim is not only to show that the MOAO technical challenges can be solved, but also that multiplexed AO-assisted spectrographs can deliver actual science. Raven, officially started on February 1 2010 and will involve HIA, Subaru and Canadian companies. The total available funding is about $6M over three years (which is very significant), making the development of a scientific-grade demonstrator much more realistic.

Regarding sky experiments, further characterization of the sodium layer is needed before LGS AO can be applied to future AO instruments such as IRMOS; the UBC group with its LZT is ideally positioned to carry out that critical work. HIA and UVic are also collaborating to design advanced AO simulation software that is necessary for predicting the performance of those systems and optimize them. HIA and UVic have also partnered with Subaru and INO to develop more advanced WFSs. HIA Victoria and UVic have partnered with HIA Penticton and Lyrtech to develop real-time computers (RTCs) able to handle the control of TMT-class AO systems. That very successful collaboration harnessed radio-astronomy expertise in designing computationally very intensive correlators on large radio telescopes, as well as Lyrtech's industrial experience in designing custom real-time computing architectures.

3. CONCLUSION AND SUMMARY

AO is widely recognized as critical in achieving science with large telescopes. Canada has established itself as a world leader in the field, providing Canadian astronomers with the best AO facilities. To maintain that leadership we need, at the same time, to i) design and build new facility instruments for TMT and Gemini, ii) provide experimental lab support for those developments, and iii) carry out R&D aimed at more advanced AO concepts. All that is only possible when HIA, Canadian universities and Canadian industry work together, in collaboration with key international partners.

HIA has the experience, the core AO expertise, the critical mass of engineers and the institutional memory to lead the development of major AO facilities, as well as to undertake fundamental AO research. That capability should be preserved.

University groups at UBC, UdM, UL and UVic provide valuable support to our AO developments by developing new techniques and by running lab and field experiments. They should be encouraged to continue to do so. Significant investments of public funds, as well as talented individuals, have made the UVicAOLab one of the best AO lab in the world, and a key part of astronomical AO developments in Canada. Its short-term future looks bright, but the long-term future of the Lab and of its staff remains tied to finding continuing funding, which is not yet secured. That uncertainty constitutes a risk to Canada's leadership in AO. Key to our success in AO is also the training of young AO scientists and AO-savvy astronomers. Closer interactions between engineering and astronomy departments should therefore be strongly encouraged whenever and wherever possible.

Canadian companies are poised to play an increasing role in astronomical AO. They should be encouraged to contribute their industrial expertise to the design and fabrication of major AO sub-systems. Companies known to have an interest in AO include INO, ComDev, TelOps and Lyrtech; others should also be encouraged.

The future of AO also depends on the development of new key components, such as deformable mirrors and low-noise, high-speed detectors. Those require R&D capabilities which are only available in industry and at major universities. In order to stimulate interest, it will be critical to link those developments to non-astronomical applications (such as medical diagnostics or telecommunications) which could provide strong marketing opportunities and offer possibilities for funding, at least partly, from non-astronomical sources.

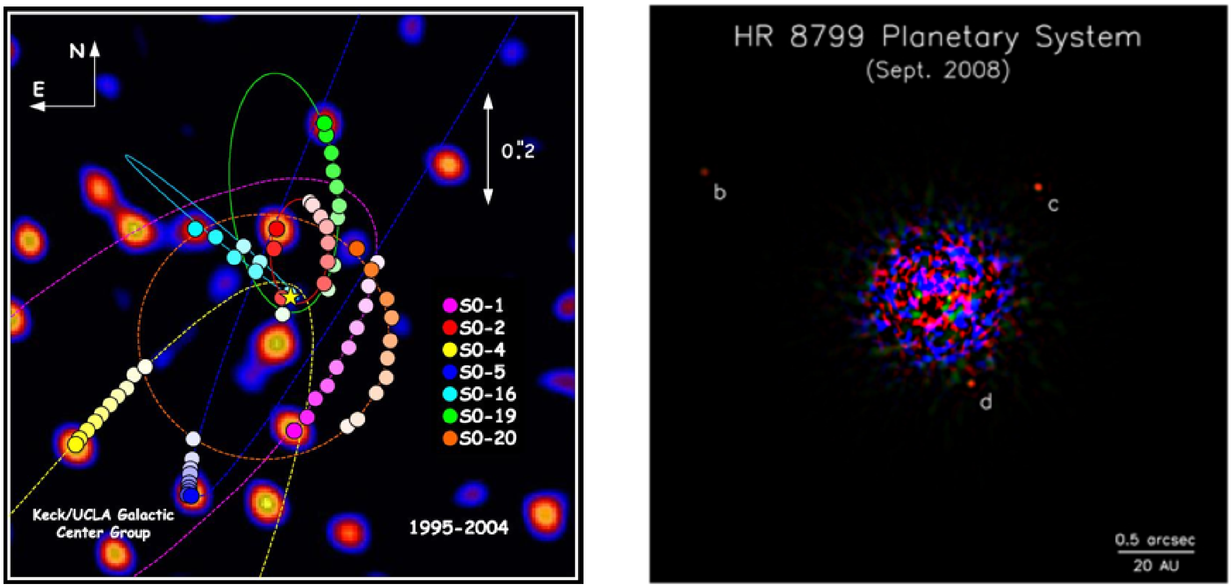

Fig. 1.— Left: Diffraction limited image of the central 1x1 arcsec of our Galaxy. Overlaid are the orbits of the star inferred from their measured positions over the last 13 years. These orbits provide the best evidence yet for a supermassive black hole, which has a mass of 4.1 million times the mass of the Sun (Ghez et al. 2008). Right: High contrast image of HR 8799, the first extra-solar planetary system ever imaged, initially discovered with Altair, and subsequently observed at Keck. ”b” is the 7 Jupiter-mass planet orbiting at about 70 AU, ”c” is the 10 Jupiter-mass planet orbiting the star at about 40 AU (Marois et al. 2008).

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TABLE 1
List of acronyms

ACURA	Association of Canadian Universities for Research in Astronomy
AO	Adaptive Optics
BCKDF	British Columbia Knowledge Development Fund
CCD	Charged-Coupled Device
CFHT	Canada-France-Hawaii Telescope
CFI	Canadian Foundation for Innovation
DAO	Dominion Astrophysical Observatory
ESO	European Southern Observatory
FOV	Field Of View
FWHM	Full-Width at Half-Maximum
GLAO	Ground-Layer Adaptive Optics
GPI	Gemini Planet Imager
HIA	Herzberg Institute of Astrophysics
HRCAM	High-Resolution Camera
HST	Hubble Space Telescope
IfU	Integral field Unit
INO	Institut National d'Optique
IRCS	Infrared Camera and Spectrograph
IRMOS	Infra-Red Multi-Object Spectrograph
JWST	James Webb Space Telescope
LBT	Large Binocular Telescope
LGS	Laser Guide Star
LZT	Large Zenith Telescope
MAD	Multi-Conjugate adaptive optics Demonstrator
MCAO	Multi-Conjugate Adaptive Optics
MOAO	Multi-Object Adaptive Optics
NFIRAOS	Narrow-Field Infra-Red AO System
NIFS	Near-Infrared Integral Field Spectrometer
NSERC	Natural Sciences and Engineering Research Council of Canada
PDR	Preliminary Design Review
PFI	Planet Finder Instrument
PSF	Point Spread Function
R&D	Research and Development
RTC	Real-Time Computer
SOAR	Southern Astrophysical Research Telescope
TMT	Thirty Meter Telescope
UBC	University of British Columbia
UdM	Université de Montréal
UL	Université Laval
UVic	University of Victoria
VLOT	Very Large Optical Telescope
VLT	Very Large Telescope
VOLT	Victoria Open-Loop Testbed
WFS	Wave-Front Sensor