# CFHT Large Programs
## Second Call - [2010B - 2012B]
### Deadline: 1 Feb 2010 - 24:00 UTC

<table>
<thead>
<tr>
<th>Title</th>
<th>Thermal Emission of Transiting Exoplanets (TETrEs): Probing the Diversity of Hot Jupiter Atmospheres with Multi-Wavelength Precision Photometry</th>
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<td>Abstract</td>
<td>Of the growing population of 'hot Jupiters', those caught in transit and secondary eclipse are best suited for detailed characterization. Thermal emission from several such planets has now been measured, first with Spitzer and HST and later with ground-based telescopes. We have used CFHT/WIRCam in an optimized mode to detect the secondary eclipses of four hot Jupiters so far in the near-infrared, at or near the planets' blackbody peaks. Our measurements are the most precise yet from the ground, and include the first ground-based H and J detections. The results to date suggest a remarkable diversity of atmospheric characteristics among these worlds. We propose to build upon these exciting recent findings and explore that diversity further by targeting all extra-solar planets favorable for ground-based secondary eclipse detections in a CFHT Large Program using WIRCam. Our multi-wavelength observations will reveal the planets' dayside temperatures, probe the redistribution of heat at various atmospheric depths, search for temperature inversions, and provide constraints on the planetary energy budgets and orbital eccentricities, thus dramatically advancing our understanding of the underlying physics. The proposed Large Program, exploiting the large field-of-view and on-chip guiding of WIRCam and the unprecedented photometric precision we have already demonstrated with it, will position CFHT at the forefront of extra-solar planet research. It fills a unique niche in the near-infrared, in the absence of NICMOS on HST and prior to the launch of JWST, and will complement longer-wavelength observations with warm Spitzer and optical observations with CoRoT and Kepler.</td>
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| Total number of hours requested | 168 |
| Hours per agency: | Canada 84, France 84, Hawaii, Taiwan |

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SCIENTIFIC JUSTIFICATION

Since the surprising 1995 discovery of a “hot Jupiter” around the Sun-like star 51 Peg, many others like it have been identified. These planets are so close to their stars that tides are expected to have synchronized their rotational and orbital periods (Lin et al. 1996). The result is that they should have a permanent dayside that is continually insolated by their stars, and a nightside that is only heated by atmospheric advection from the dayside. Some hot Jupiters are fortuitously aligned such that they not only transit their parent stars along our line-of-sight, but also pass behind their stars during the course of an orbit. These secondary eclipses allow direct measurements of the planets’ dayside emission, thus the temperature, when observed in the infrared. In the past few years, secondary eclipses of several exo-planets have been detected, first with Spitzer at wavelengths $>3\mu m$, thus longwards of their blackbody peaks (Demming et al. 2005; Charbonneau et al. 2005), and later in the near-infrared (at $\sim 2 \mu m$) with Hubble (Swain et al. 2009). Most recently, several groups, including ourselves, have reported ground-based near-infrared detections (de Mooij & Snellen 2009; Sing & Lopez-Morales 2009; Gillon et al. 2009; Croll et al. 2010a, 2010b, 2010c, 2010d), opening up a new avenue of exploration.

Thermal emission measurements of hot Jupiters to date (see below) suggest a remarkable diversity of atmospheric characteristics among these worlds. We propose to build upon the exciting recent findings and explore that diversity further by targeting all extra-solar planets favorable for ground-based secondary eclipse detections in a CFHT Large Program using WIRCam. The primary science goals of our program will be: to help us understand the energy budgets of these planets, especially when combined with constraints at other wavelengths from Spitzer, CoRoT and Kepler, to determine the overall dayside bolometric luminosity and the fraction of heat that is advected to the nightside, to understand the redistribution of heat at different atmospheric depths and pressures near their blackbody peak, and finally to help us to understand the underlying physics that dominates the reradiation and advection of heat in these planets’ atmospheres.

Other scientific goals include searching for temperature inversions in the upper atmosphere of these exotics worlds, identifying the molecular make-up of the stratospheric absorbers that cause such inversions, and looking for brightness temperature changes due to storms in multi-epoch eclipse observations. Our observations will also constrain precisely the planets’ orbital eccentricities; for those planets that turn out to be eccentric (such as WASP-12b, as discussed below), our observations will lead to limits on the much-discussed tidal quality factor (the tidal $Q$), and constrain whether the inflated radii of many hot Jupiters could be due to tidal heating. Our program comes at an opportune time; in the absence of NICMOS on HST, and before the JWST era, our program will provide the near-infrared complement to longer-wavelength observations with warm Spitzer and shorter wavelength optical observations with CoRoT (in which several members of our team play integral roles) and Kepler.

We propose to observe as many hot Jupiters as possible in as many near-infrared bands as is practical with WIRCam on CFHT. We have already demonstrated that CFHT/WIRCam is able to provide the best photometry of hot Jupiter eclipses in the J, H & Ks bands of any telescope on the ground. This precision has allowed us to obtain the first ground-based detections of a secondary eclipse in the J and H bands. Our proposed Large Program will exploit this demonstrated superior precision and position CFHT at the forefront of a wide swath of extra-solar planet research, where it will make a profound impact.

Why the Near-Infrared? The near-infrared (NIR) is at or near the blackbody peak for the vast majority of hot Jupiters. Yet, we currently have precious few trustworthy constraints in this wavelength range. That nearly everything we know about hot Jupiter atmospheres is from the Wien tail of their blackbody is worrying, if not disturbing.

The usefulness of NIR constraints on hot Jupiter atmospheres is shown in Fig. 1. The top panel shows the planet-to-star flux ratio, which is the observationally measured quantity. The flux ratio increases dramatically in the mid-IR, where Spitzer IRAC is sensitive. Flux ratio plots overemphasize the importance of the mid-IR, however. The middle panel recasts the model planetary emission in flux per micron units. This clearly shows that it is in the NIR that hot Jupiters are brightest – the vast majority of the planetary flux is emitted blueward of the IRAC bands. Therefore, detections of planetary flux in the NIR put much stronger, more model-independent, constraints
on the dayside bolometric flux (Barman 2008). In addition, the bottom panel shows the model brightness temperature as a function of wavelength. The brightness temperature is essentially the temperature at the optical depth $=2/3$ surface. In the NIR, one clearly probes higher atmospheric pressures, because the JHK bands are windows in the opacity of water vapor. By comparing flux ratios between the NIR and mid-IR, we will get a much better handle on the temperature structure of these atmospheres, and place better constraints on the presence or absence of temperature inversions (Fortney et al. 2008, Burrows et al. 2008).

One of the most-discussed aspects of hot Jupiter atmospheres is the redistribution of heat from the presumably permanently insolated dayside to the cool nightside. We choose to parameterize this redistribution by the so-called reradiation factor, $f$, following the Lopez-Morales & Seager (2007) definition ($f=0.50$ for dayside emission only, and $f=0.25$ for very efficient redistribution of heat to the nightside and isotropic reradiation). It is important to note, that the redistribution of heat is a \textit{wavelength dependent quantity}, with different levels of redistribution at different depths of the atmosphere. Thus even thermal phase curve measurements from observations at a single wavelength, that provide a planet’s day and nightside emission, only reveal how efficiently the planet redistributes heat at the level of the photosphere probed by that particular wavelength of observation. Thus, to truly understand heat redistribution in hot Jupiters, one needs multi-wavelength constraints that provide an estimate of the bolometric dayside luminosity. Although mid-infrared constraints help, the best-place to determine their bolometric luminosity is in the NIR, near the blackbody peak.

There is a theoretical rationale for why we would expect redistribution to be more efficient in the NIR than at longer wavelengths. The redistribution of heat in hot Jupiter atmospheres can be thought of, to first-order, as the ratio of the radiative to advective timescales. The radiative time-scale (how quickly the planet reradiates the incident stellar flux: $\tau_{rad}$) is thought to be proportional to $\tau_{rad} \sim \frac{c_P P}{3g \sigma T_\text{eff}^4}$ (Showman & Guillot 2002), where $c_P$ is the specific heat capacity, $P$ and $T$ are the temperature and the pressure, $\sigma$ is the Stefan-Boltzmann constant, and $g$ is the gravitational acceleration of the planet. The advective timescale on the other hand (how quickly the planet advects heat to the nightside: $\tau_{adv}$) can be approximated by the radius of the planet, $R_P$, divided by the windspeed, $U$: $\tau_{adv} \sim \frac{R_P}{U}$ (Showman & Guillot 2002). Planets with short radiative timescales compared to their advective timescales will harbor inefficient redistribution, thus bright dayside emission, while planets for which the two timescales are comparable will feature efficient redistribution of heat to their nightsides. At low pressures it is expected that $\tau_{rad}$ is much shorter than $\tau_{adv}$, so that at wavelengths where low pressures are probed (such as the mid-IR, where water opacity is generally high) the planet’s emission will be bright due to the short radiative timescale, an effect further enhanced if the upper atmosphere is hot due to a temperature inversion. As one probes deeper into hot Jupiter atmospheres and to higher pressures, e.g., at wavelengths that correspond to minima in the water opacity, the radiative timescale will increase and may become of similar order to the advective timescale (Seager et al. 2005; Fortney et al. 2008). Here is another way to think about this: at low pressures (probed by the mid-IR) wind speeds will have to be on the order of dozens of kilometers per second to efficiently advect the incoming stellar irradiation, while at higher pressures (probed by the NIR) windspeeds only have to be on the order of a few kilometers per second for efficient redistribution (Fortney et al. 2008). Thus in the JHK bands we may expect more efficient redistribution, and the NIR emission may be depressed as the depths we probe may be more homogenized than the upper atmospheres of these planets.
Diversity of Hot Jupiter Atmospheres

Fortney et al. (2008) suggested that hot Jupiters would fall into two broad classes based on the incident stellar flux. The hottest, most highly irradiated planets, dubbed the pM-type, would have large day/night asymmetries, thus brighter secondary eclipses, and would display temperature inversions, with water bands in emission rather than absorption. The merely warm pL-type planets (with equilibrium temperatures of $\sim 1000K$) would feature small day/night asymmetries, thus smaller secondary eclipses, and would display temperature inversions due to atmospheric temperatures that decline monotonically with altitude. The dividing line was thought to be at an incident stellar flux of $\sim 10^9$ erg/s/cm$^2$, since above this value TiO and VO would be in gaseous form in their stratospheres and would absorb and immediately re-radiate the incident radiation (Hubeny et al. 2003; Burrows et al. 2007; Fortney et al. 2008).

The first two hot Jupiters with sufficiently precise measurements were indeed consistent with this picture: HD 209458 showed a temperature inversion and water emission bands (Knutson et al. 2008; Burrows et al. 2007) while HD 189733 displayed a small day/night asymmetry (Knutson et al. 2007), implying efficient advection, and no temperature inversion (Charbonneau et al. 2008). However, since then the list of exceptions to this simple classification has been growing. TrES-3b is highly irradiated but does not display a temperature inversion (Fressin et al. 2009; Croll et al. 2010b), while XO-1b receives low levels of stellar insolation but shows a temperature inversion (Machalek et al. 2008). Other planets, such as HAT-P-1b (Todorov et al. 2010), seem to frustratingly straddle the dividing line. Thus, it is clear that the properties of hot Jupiters span a wider range than our simple theories suggested.

**Results To Date.** We have used CFHT/WIRCam in an optimized mode to detect the secondary eclipses of at least four hot Jupiters so far (see Figures 2, 4, 8, and 7). As is so often the case with exoplanets, the NIR results highlight the incompleteness of our present understanding.

TrES-2b is a highly irradiated hot Jupiter in a $\sim 2.5$
We detected its secondary eclipse with a depth of 0.054 ± 0.012% (4σ) in the Ks-band (Croll et al. 2010a; see Fig. 2), corresponding to a dayside brightness temperature of \( T_B \sim 1580 \) K. Our eclipse depth, when combined with Spitzer/IRAC observations of O’Donovan and collaborators, suggests that despite this planet’s high irradiation it exhibits a relatively isothermal pressure-temperature profile, efficient day to night-side heat redistribution, and harbors at best a weak temperature inversion due to chemical species other than TiO/VO.

We have also detected the secondary eclipse of the even more highly irradiated TrES-3b in Ks-band with a depth of 0.117 ± 0.016% (7σ; Fig. 4; Croll et al. 2010b). Our 3σ limit on its H-band thermal emission is 0.049%. Similarly to TrES-2b, our results for TrES-3b indicate a relatively isothermal dayside pressure-temperature profile, very efficient day-to-nightside heat redistribution and nearly isotropic radiation. However, the best-fit model from our Ks-band detection and from the longer wavelength data from Spitzer – a model that does not feature a temperature inversion and probes deep into the atmosphere in the H-band through gaps in the water opacity – is highly discrepant with our strict H-band upper limit. This result underlines the importance of observations in multiple NIR bands, in addition to Spitzer photometry. 1

For these two planets, our CFHT/WIRCam findings are broadly consistent with theorists’ expectations that hot Jupiters would have efficient heat redistribution at atmospheric depths probed in the NIR. However, our very recent (2009 Dec 26-28) observations of another highly irradiated hot Jupiter, WASP-12b, which orbits its F-type host in just \( \sim 25 \) h, provide a dramatic contradiction. We not only detected the thermal emission of WASP-12b Ks-band with a confidence approaching 20σ, but also obtained the first detections of a secondary eclipse in the H & J bands (Croll et al. 2010c; Fig. 8)\footnote{Our Ks-band eclipse depth is in sharp contrast to the de Mooij & Snellen (2009) result, who noted that their measurement suffered from large systematic noise. Our detection is higher S/N and, more importantly, suffers from fewer systematics - a distinct advantage CFHT/WIRCam offers.}. The Ks & H-band eclipses are very deep, indicative of very inefficient heat redistribution at these wavelengths. Interestingly, the J-band eclipse depth is much smaller, and suggests we could be looking through a hole in the water opacity to a well-homogenized level of the atmosphere with a much longer radiative timescale (see Fig. 6). What’s more, despite this planet’s \( \sim 1 \) d orbital period, all three eclipses are best fit at a phase different than 0.50, thus indicating an eccentric orbit. Given that WASP-12b’s orbit should have circularized long ago if its tidal quality factor, \( Q \), is similar to Jupiter’s, we should be able to place a constraint on \( Q \) and determine whether tidal luminosity accounts for its “puffed-up” radius.

Lastly, we have also detected the secondary eclipse of WASP-3b in Ks-band on two occasions (Croll et al. 2010d; Figure 7). WASP-3b is highly irradiated, similarly to TrES-3b and TrES-2b. Despite this fact, this planet displays very inefficient redistribution of heat at the depths probed by our Ks-band observations. In fact, WASP-3b shines more brightly than would be ex-

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1Our Ks-band eclipse depth is in sharp contrast to the de Mooij & Snellen (2009) result, who noted that their measurement suffered from large systematic noise. Our detection is higher S/N and, more importantly, suffers from fewer systematics - a distinct advantage CFHT/WIRCam offers.
Figure 5: Dayside planet-to-star flux ratios (left) and dayside flux at the planet’s surface (right). The Ks-band point (∼2.15 µm) is our own, while the Spitzer/IRAC points are from Fressin et al. (2009). We also denote our H-band 3σ upper limit, along with the 90% upper-limits obtained by Winn et al. (2008) (downward arrows). Blackbody curves for isotropic reradiation (f=0.25; $T_{\text{eq}}\sim$1654 K; blue dashed line) and for dayside only emission (f=0.32; $T_{\text{eq}}\sim$1724 K; red line) are also plotted. We also plot one-dimensional, radiative transfer spectral models (Fortney et al. 2006, 2008) for various reradiation factors and with and without TiO. We plot models with reradiation factors of f=0.29 with and without TiO (red and cyan lines, respectively), and with close to isotropic reradiation (f=0.29) with and without TiO (purple and green lines, respectively). Both models with TiO display temperature inversions. The models on the left panel are divided by a stellar atmosphere model Hauschildt (1999) of TrES-3 using the parameters from Sozzetti et al. (2009) ($M_*=0.928 M_\odot$, $R_*=0.829 R_\odot$, $T_{\text{eff}}=5650$ K, and log $g=4.4$). We plot the Ks and H-band WIRCam transmission curves inverted at arbitrary scale at the top of both panels (dotted black lines).

Figure 6: Dayside planet-to-star flux ratios (top) and dayside flux at the planet’s surface for WASP-12 (bottom). Blackbody curves for isotropic reradiation (f=0.25; blue dashed line) and for dayside only emission (f=0.50; red line) are also plotted. We plot the Ks, H & J-band WIRCam transmission curves inverted at arbitrary scale at the top of both panels (dotted black lines).

Figure 7: CFHT/WIRCam photometry of the secondary eclipse of WASP-3b observed on different days both in the Ke-band. The figure is otherwise identical to Figure 2.
Figure 8: CFHT/WIRCam photometry of the secondary eclipse of WASP-12b observed on different days in the Ks, H & J-bands. This reduction is preliminary. The panels are otherwise identical to Figure 2.

Figure 8: CFHT/WIRCam photometry of the secondary eclipse of WASP-12b observed on different days in the Ks, H & J-bands. This reduction is preliminary. The panels are otherwise identical to Figure 2.

Expected from even dayside only emission; not only does there appear to be inefficient advection to WASP-3b’s nightside at the atmospheric depth we probe, but also inefficient advection from the sub-stellar point even to other areas of the dayside illuminated face. Since we have detected two eclipses of WASP-3b in the same NIR band, we can also look for temporal variability in the eclipse depths, indicative of brightness temperature changes due to storms. Such storms have been theoretically predicted by dynamical atmospheric models of hot Jupiters with simplified radiative transfer. Examples include the 2D shallow water models of Langton & Laughlin (2008) and more recently the 3D shallow water simulations of Menou & Rauscher (2009); the latter predict brightness temperature variations $\sim 100 K$.

Interestingly the eccentric hot Neptune GJ 436 displays possible signs of variability at 8.0 $\mu$m (Laughlin et al. 2010). Also, for HD 189733b although Agol et al. (2009) have placed 10% upper limits on its eclipse variability, other researchers have shown a number of possible detections of eclipse variability for this planet that approach 3$\sigma$ (as reported in Madhusudhan & Seager 2009). If these variations are real (rather than due to systematic errors), then storms arising from varying levels of stellar insolation provide a likely explanation. We find that in the case of WASP-3b, the two eclipses we observed have depths identical to within 300 K.

Need for a Large Sample  The implication from our CFHT/WIRCam program to date is that hot Jupiters are as diverse and mysterious as ever. Some highly irradiated hot Jupiters display very efficient redistribution of heat at the depths probed by our observations, while others do not despite similar levels of irradiation. This is not to say that we are not making significant progress. Our NIR observations have revealed that the first two hot Jupiters we discussed, TrES-2b and TrES-3b efficiently redistribute their heat and emit nearly isotropically, while the latter two – WASP-12b and WASP-3b – harbor strong day-night asymmetries. Our observations of WASP-12b are particularly valuable; by probing deep into its atmosphere with Ks, H & J-band observations we have shown that the underlying physics deep in a hot Jupiter’s atmosphere may be markedly different than what is happening at the surface.

The path forward for understanding the energy budgets and the underlying physics of hot Jupiters is via multi-wavelength constraints on their thermal...
emission near the blackbody peaks. Our proposed program and our preliminary target list will facilitate this endeavor. For example, CoRoT-1 and CoRoT-2 should display very prominent emission and thus we hope to detect their thermal emission in the J, H & Ks bands; as these planets already have optical constraints from CoRoT and have been or will shortly be observed with Spitzer at >3 µm, we should obtain a thorough understanding of their energy budgets. CoRoT-5 receives lower stellar insolation and is near the predicted dividing line between the hottest (pM) and merely warm (pL) classes of hot Jupiters; the comparison of this planet’s Ks-band emission with the rest of our sample should prove enlightening. Our observations of XO-3 should provide synergistic NIR constraints to the warm Spitzer program that will shortly observe its full thermal phase curve in the 3.6 and 4.5 µm IRAC channels (PI Machalek); we have already entered into a collaboration with this group in anticipation of our observations. Lastly, there is an additional known planet in the HAT-P-13 system, other than the hot Jupiter HAT-P-13b that is in a so-called tidal fixed point state; a constraint on the eccentricity of HAT-P-13b will reveal very precise limits on the tidal quality factor, $Q$, the tidal Love number, $k_2$, and perhaps most interestingly the mass of this hot Jupiter’s core (Batygin et al. 2009). Also, if the tentative signs of eclipse variability from Spitzer observations discussed above prove to be real, we may follow-up a few targets with the largest thermal emission to see if the storms presumably causing this variability penetrate deep in the atmospheres of these worlds. Observations of newly announced hot Jupiters over the next few years, including those from Kepler, are sure to prove exciting and informative. In summary, observations of this larger sample of hot Jupiters are essential to investigate the diversity of their atmospheres, to inform theoretical modelling, and to develop a global picture of the underlying physics of these exotic worlds.

REFERENCES

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Croll, B. 2006, PASP, 118, 1351
Croll, B., et al. 2010c, in preparation
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\(^2\)Available at http://www.astro.utoronto.ca/~croll/preprint.html
TECHNICAL JUSTIFICATION

Our proposed Large Program builds on our successful pioneering PI program approved as the top Canadian proposal at CFHT in the 2009A semester (09AC14 - Croll). That program and the follow-up program in 2009B proved that sub-millimagnitude photometry is possible in the NIR at CFHT in the J, H & Ks-bands. Our analysis of one 2009A Ks-band photometric dataset indicates that we are able to achieve a root-mean-square (RMS) precision of $\sim 7.5 \times 10^{-4}$ per 60 seconds. This precision is stable on the timescale of hours and is relatively free of red noise as evidenced by the fact that it bins down near the one-over-the-square-root of the bin size expectation for gaussian noise (Figure 9). Follow-up observations in 2009B in H and J indicate that we are able to achieve RMS precisions of $\sim 9 \times 10^{-4}$ and $\sim 8 \times 10^{-4}$ per minute in these two bands, respectively. To our knowledge these are the most precise photometric observations returned from the ground in each of these three bands to date. Photometry of this accuracy and stability has allowed us to detect thermal emission from a number of hot Jupiters in the Ks-band with great confidence - our WASP-12b detection is in excess of 20$\sigma$. Also, we have returned the first H and J-band detections of the thermal emission of a hot Jupiter. We plan to use an identical technique for this LP and summarize this strategy here via which we hope to detect the thermal emission of a large sample of hot Jupiters in the J, H, Ks and possibly other NIR-bands.

WIRCam’s “Stare mode”  As a result of the impressive photometric accuracy we were able to demonstrate using CFHT/WIRCam in our 2009A classical observations, our technique has been integrated into Queued Service Observing (QSO) at CFHT. The technique we pioneered in 2009A is now referred to as “Staring Mode” in QSO-parlance. In this mode the telescope stares at the same point in the sky for several hours while WIRCam takes short full-mosaic exposures of typically 3 to 5 seconds; the 21 arcmin field-of-view of WIRCam allows one to observe the target star as well as a great number of nearby reference stars. The duty-cycle for these observations is usually just under 50% once overheads are taken into account. To avoid detector saturation the telescope is defocused (usually to 1 to 2 mm) resulting in the stellar flux of each target being spread over a defocused annulus 10-20 pixels in diameter on the array. This defocus has the added side benefit of improving the precision we are able to achieve by reducing the impact of interpixel variations and diluting the weight of the uncertainty of each pixel’s flat field response, thus minimizing the flat field error.

**Keys to High Precision** The key to achieving such high precision are the unique properties of WIRCam on CFHT and our data-reduction pipeline. CFHT/WIRCam benefits from: 1) the photometric sky of Mauna Kea; 2) the ability to defocus the telescope to minimize flat fielding errors and interpixel variations; 3) the on-chip guiding and focusing of WIRCam to keep the flux on the same pixels and the PSF relatively constant; 4) the rapid read-out to avoid detector saturation; 5) the wide field-of-view that allows many reference stars to be observed 6) and finally the stability of the instrument with fringeless backgrounds.

Even with the impressive conditions on Mauna Kea and the advantages of WIRCam, the accuracy that results from performing aperture photometry on just our target star is nowhere near that required to achieve our science goals. Light curves obtained with this method display significant, systematic variations in intensity (see the top panel of Figure 10), possibly due to changes in atmospheric transmission, seeing and airmass, guiding errors and/or other effects. Luckily, WIRCam’s wide field-of-view also allows us to perform accurate aperture photometry on numerous reference stars (usually 60 - 100 similarly bright reference stars), and these reference stars display near-identical systematics to that of our target. By correcting the flux of our target star with usually ~10 nearby reference stars that display the smallest deviations in flux from that
of our target star outside of the expected secondary eclipse, we are able to drastically improve the RMS of our photometry. For our observations of TrES-2b [K~9.8] in Ks-band, correcting our target lightcurve with 10 nearby reference stars improves the precision by more than a factor of twenty (the precision improved from $141 \times 10^{-4}$ to $7 \times 10^{-4}$ per 60 seconds). Similarly correcting our target flux with numerous reference stars has proved to be similarly advantageous in H & J-band as evidenced by sub-millimagnitude precision per minute achieved in these two bands quoted above. We have thus demonstrated that we are able to achieve photometric precision with a scatter less than 1 part in 1000 on minute-long timescales on numerous occasions in Ks, on both occasions that we attempted this method in H-band, and on the one occasion we observed in the J-band. We thus believe it is a conservative assumption to assume we will achieve similar precision for our proposed observations using an identical method as part of this LP.

Weather Constraints It should be noted that photometric conditions are critical for achieving sub-millimagnitude photometry. Previous staring sequences taken under photometric conditions show flux variations of less than 1% on timescales of <10 minutes and slow drifts of ≈1% per hour (not correlated with airmass). As these variations fortunately affect both the target and reference stars simultaneously, they can largely be normalized out. However, as was recently shown by observations of an occultation of Pluto with WIRCam in 2008 observed under non-photometric conditions (Boissel et al. 2008), it is difficult to achieve sub-millimagnitude precision under adverse conditions. We thus emphasize that the science goals of this project require favourable conditions.

Our target list and modelled observations We list our proposed targets for the 2010B, 2011B and 2012A semesters in Table 1, and discuss these selections further in the Observing Strategy section. For each target we will need to observe in-eclipse and out-of-eclipse portions to provide an adequate reference baseline from which to measure the drop in flux due to the loss of planetary emission. For the average target in our program we will spend just over 40% observing the in-eclipse portion of the lightcurve, and just under 60% observing the out-of-eclipse portion. Our targets will require 3-8 hours of observations per target per NIR-band. Our observations must also be precisely scheduled to ensure the secondary eclipses occur at low air mass and near the middle of the night so as to ensure adequate out-of-eclipse baselines. We have confirmed that there are numerous suitable eclipse windows for each of our targets such that we can realistically schedule our observations assuming WIRCam is on the telescope ~45 nights per semester.
For the modelled observations that follow we calculate the dayside temperature of our planets, $T_p$, as: $T_p = T_{eff}(R_*/a)^{1/2} \times (f(1 - A_B))^{1/4}$. The dayside temperature thus depends on a number of well-established factors such as the stellar effective temperature $T_{eff}$, the radius of the stellar host $R_*$, and the planet’s semi-major axis $a$. We assume a Bond albedo of zero, consistent with observational results from other hot Jupiters (Charbonneau et al. 1999; Rowe et al. 2008), and with model predictions (Burrows et al. 2008). The most important variable is the reradiation factor, $f$. For the modelled observations that follow we assume a reradiation factor of $f=0.4$ (or modest redistribution of heat to the nightside). For planets that radiate nearly isotropically in the NIR, such as TrES-2b and TrES-3b, our simulations will overestimate their dayside temperature and the resulting predicted emission. For planets such as WASP-3b and WASP-12b, however, this will result in a significant underestimate of their predicted thermal emission during their secondary eclipses. We therefore believe our choice of reradiation factor is a suitable compromise.

For each one of our targets we calculate a realistic secondary eclipse model using the Mandel & Agol (2002) algorithm given the dayside temperature, $T_p$, of the planet and the effective temperature of the stellar host. To ensure our simulations are as realistic as possible we have modelled our Ks, H and J-band observations with the actual residuals from our best-fit eclipse models from our previous (2009A/2009B) observations. Thus for each simulation that follows we first determine the residuals from our best-fit model of an observation in the appropriate band (we use our TrES-2 observations in Ks, our TrES-3 observations in H and our WASP-12 measurements in J). We then add these residuals to the modelled secondary eclipse of our proposed target, and then submit these simulated data to our actual fitting routines. Thus our simulated data should not only display the exact same noise properties as our data, but should also suffer from the same biases, if any, of our fitting routines. Table 1 lists our tentative targets for the 2010B, 2011B and 2012A semesters as well as the predicted significance of detections (number of $\sigma$) for our observations; we present our simulated observations of one of our proposed targets, CoRoT-2b, in Figure 11. Table 1 also lists the NIR-bands that we plan to observe each target in, the right ascensions and declinations of our targets, the total time per observation (the sum of the in-eclipse and out-of-eclipse portions), and the semester (A or B or both) that the target will have a suitable eclipse at low airmass in the middle of the night. We note that our proposed targets span a a wide RA-range, as should newly announced hot Jupiters (although the Kepler and CoRoT planets will be closely clustered around the other CoRoT and Kepler planets listed in Table 1).

**Saturation Limits** To avoid saturation the limiting magnitudes in the J, H & Ks-bands on WIRCam are $J<10.0$, $H<10.3$ and $Ks<9.5$, assuming $\sim 3$ second exposure times and that the telescope has been fully defocused. In practice, we have found these estimates to be accurate to within $\pm \sim 0.3-0.5$ mag depending on seeing. For our tentative targets discussed in Table 1 that are brighter or close to this limit we plan to observe them in other WIRCam filters of a similar wavelength. For instance, instead of the Ks filter we plan to observe using the $K_{CONT}$ filter, which can observe stars up to two magnitudes brighter than in Ks. Instead of the H-band filter we plan to observe in the narrow-band CH$_4$ (on or off) filters. We will perform small engineering runs by observing our target in these filters to ensure they return photometry of similar precision to the J/H/Ks filters. We also emphasize that our H-band TrES-3b observations and our Ks-band WASP-3 observations suffered from some saturated pixels and this did not significantly affect the precision we were able to achieve.
OBSERVING STRATEGY

Over the course of this proposed Large Program, we expect to observe 10-20 hot Jupiter host stars in up to three or more bands in the NIR. Hot Jupiters with the most prominent predicted thermal emission will be observed in as many bands as are feasible, while hot Jupiters with weaker predicted thermal emission will be observed only in the most favourable band (presumably the Ks-band). For the planets with weaker predicted thermal emission, if their dayside emission turns out to be stronger than predicted, such as would be the case for a planet that redistributes very little of its heat to the nightside at that wavelength, or due to an emission rather than absorption feature for instance, that target will then be followed up in additional bands.

Unfortunately, it is difficult to compile a complete target list for our entire program at this time, due to the rapid pace of discoveries and new announcements of transiting exoplanets. 10 transiting planets were announced in 2009, and at the time of writing (not even an entire month into 2010), 5 transiting planets have already been announced this year from the Kepler mission. Given the impressive accuracy of Kepler (Borucki et al. 2009), and CoRoT (Baglin et al. 2006) and the track-record of the ground-based transit searches (Super-WASP [Pollacco et al. 2006] and HAT [Bakos et al. 2002; 2004] in particular) we fully expect the rapid pace of announcements of new transiting exoplanets to continue. Many of the recently announced exoplanets, WASP-12b being an obvious example, are the hottest and most inflated transiting planets and are thus the most advantageous for our program. Nonetheless, there are enough suitable candidates at this point in time, however, to provide a tentative target list. We discuss this list below.

We will provide a complete list of ephemerides at the start of each semester to facilitate scheduling, as we have done before in 2009A and 2009B PI programs. We will update these ephemerides approximately two weeks prior to each and every WIRCam run in the light of updated information about our targeted hot Jupiters, or in the case of newly announced hot Jupiters with particularly prominent thermal emission. The experience from our current CFHT program has shown that continually updating our target list in the lead-up to a WIRCam run is imperative to ensure we observe the most exciting targets with the most compelling NIR emission.

We have requested 36, 48, 36 and 48 hours in the 2010B, 2011B, 2012A and 2012B semesters, respectively. A tentative target list for the 2010B, 2011B, and 2012A semesters is provided in Table 1 and shown in Figure 12. The total time required to observe targets that are visible in the 2010B and 2011B semesters is 84 hours. The total time required for targets visible in 2012A is 41 hours. Targets visible in both semesters were split between the A and B semesters for the sake of this calculation. We will likely be unable to obtain full out-of-eclipse baselines for some targets (such as TrES-4b) which have up to 4 h eclipses, and thus require nearly 8 h per band. For these targets we will observe partial eclipses. As it is likely that new hot Jupiters will be announced in the interim, the list of favourable planets we can observe should only increase. We believe this provides ample justification for our requested time allotment for the 2010B, 2011B and 2012A semesters.

We have requested 48 hours for the 2012B semester,
but have not provided a target list for that semester. The time allotment for this semester will be used to follow-up the most interesting newly announced hot Jupiters or other transiting exoplanets. Particular focus will be paid to those planets announced by Kepler and CoRoT that are favourable in the NIR and that have optical constraints or even albedo measurements from these two satellites. We will also possibly follow-up a select sample of planets that we have already observed in the same bandpass to search for eclipse variability, if the aforementioned tentative signs of storms from Spitzer are confirmed. The planets with the strongest thermal emission signals, such as WASP-12b, WASP-3b, CoRoT-1b, or CoRoT-2b, may be followed-up to allow us to search for as small as possible in the brightness temperature of these planets. However, we allow for the possibility that advances from observational detections or theoretical modelling may suggest that hot Jupiters subject to lower incident flux may be stormier, thus requiring us to target exoplanets subject to lower irradiation for such storms. We strongly believe that the combination of the above strongly justifies our requested allotment for the 2012B semester.

### Table 1: Proposed Targets

<table>
<thead>
<tr>
<th>Target Star</th>
<th>Proposed bands</th>
<th>Right Ascension</th>
<th>Declination</th>
<th>Time per band (hr)</th>
<th>Total time (hr)</th>
<th>Semester Visible</th>
<th>Predicted detection confidence (σ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>WASP-1</td>
<td>Ks</td>
<td>00 20 40</td>
<td>+31 59 24</td>
<td>7.0</td>
<td>14.0</td>
<td>B</td>
<td>6</td>
</tr>
<tr>
<td>CoRoT-1</td>
<td>Ks, H, &amp; J</td>
<td>06 48 19</td>
<td>-03 06 08</td>
<td>6.0</td>
<td>18.0</td>
<td>B</td>
<td>21 12 10</td>
</tr>
<tr>
<td>CoRoT-5</td>
<td>Ks</td>
<td>06 45 07</td>
<td>+00 48 55</td>
<td>7.0</td>
<td>7.0</td>
<td>B</td>
<td>6</td>
</tr>
<tr>
<td>XO-3</td>
<td>$K_{\text{CONT}}$</td>
<td>04 21 53</td>
<td>+57 49 01</td>
<td>6.5</td>
<td>6.5</td>
<td>B</td>
<td>7</td>
</tr>
<tr>
<td>HAT-P-7</td>
<td>Ks, &amp; H or $(CH_4)$</td>
<td>19 28 59</td>
<td>+47 58 10</td>
<td>7.5</td>
<td>15.0</td>
<td>A/B</td>
<td>18 10</td>
</tr>
<tr>
<td>TrES-2</td>
<td>Ks, &amp; H</td>
<td>19 07 14</td>
<td>+49 18 59</td>
<td>3.5</td>
<td>7.0</td>
<td>A/B</td>
<td>6 3</td>
</tr>
<tr>
<td>TrES-3</td>
<td>H</td>
<td>17 52 07</td>
<td>+37 32 46</td>
<td>3.5</td>
<td>3.5</td>
<td>A/B</td>
<td>6</td>
</tr>
<tr>
<td>WASP-3</td>
<td>H or $(CH_4)$</td>
<td>18 34 32</td>
<td>+35 39 42</td>
<td>4.5</td>
<td>4.5</td>
<td>A/B</td>
<td>10</td>
</tr>
<tr>
<td>CoRoT-2</td>
<td>Ks, &amp; J</td>
<td>19 27 07</td>
<td>+01 23 02</td>
<td>5.5</td>
<td>16.5</td>
<td>A/B</td>
<td>18 8 7</td>
</tr>
<tr>
<td>HAT-P-13</td>
<td>Ks</td>
<td>08 39 32</td>
<td>+47 21 07</td>
<td>7.0</td>
<td>7.0</td>
<td>A</td>
<td>7</td>
</tr>
<tr>
<td>TrES-4</td>
<td>Ks</td>
<td>17 53 13</td>
<td>+37 12 42</td>
<td>8.0</td>
<td>8.0</td>
<td>A</td>
<td>10</td>
</tr>
<tr>
<td>WASP-14</td>
<td>$K_{\text{CONT}}$</td>
<td>14 33 06</td>
<td>+21 53 41</td>
<td>6.5</td>
<td>6.5</td>
<td>A</td>
<td>9</td>
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<tr>
<td>Kepler-8</td>
<td>Ks</td>
<td>18 45 09</td>
<td>+42 27 04</td>
<td>7.5</td>
<td>7.5</td>
<td>A</td>
<td>6</td>
</tr>
</tbody>
</table>
DATA MANAGEMENT PLAN

Data processing and analysis. The proposed program will greatly benefit from the expertise we have built and the software solutions we have developed over the past two years in establishing a successful hot Jupiter secondary eclipse observation program with WIRCam. Accordingly, we are extremely well prepared to process and analyze the data promptly. During each WIRCam run, the observation logs will be reviewed daily and any data pertaining to our program will be immediately downloaded to our local server. Then, the raw data will be pre-processed using the WIRCam ʻIwi data reduction pipeline. This pipeline includes the following steps: pixel-by-pixel non-linearity flux correction, bad and saturated pixel masking, dark and sky subtraction, flat field correction, flux zero-point calibration and a rough astrometry determination. This pipeline, which was developed by a member of our team, L. Albert, has been routinely used for years for processing of WIRCam data, including data for two large programs (Bouvier et al., Willott et al.) and tens of PI programs; its efficiency and robustness have been well tested. L. Albert and B. Croll, who are both familiar with the pipeline, will be in charge of executing these steps.

The next step is the extraction of the light curve; this will be done by B. Croll with assistance from D. Lafrenière and Aldo Bonomo. As mentioned earlier, we have been working on WIRCam data sets of secondary eclipses for the past two years; in that time we have identified several sources of systematic noise and implemented the required hardware and software solutions to improve the final photometric precision (see Croll et al. 2010a for more detail). We now have in hand all the necessary software to extract the light curve from the data to the level of precision needed for this project.

The final step of analysis is fitting a secondary eclipse model and realistic background to the observed light curve; this will be done by B. Croll with assistance by Aldo Bonomo. Here again we have already developed all the necessary software as part of our previous observations. We will perform the secondary eclipse model fit using a variety of methods to ensure robust results. The foremost method will be a Markov Chain Monte Carlo method (Christensen et al. 2001; Ford et al. 2005; described for our purposes in Croll et al. 2006); as shown in Croll et al. (2010a; 2010b), this produces reliable results.

Typically, the full processing and analysis of one data set will be completed within 12-20 days of data acquisition; this will allow us to update our list of priorities for the following WIRCam run, depending on the detections and sensitivity achieved.

Hardware and data distribution. Each observation of a secondary eclipse, typically lasting for \( \sim 5 \) hours and consisting of \( \sim 1000 \) WIRCam images, will require up to \( \sim 50 \) GB of hard disk space. The pre-processing will roughly double this requirement. To handle this large data volume, we will purchase a server with 10 TB of storage capacity, mounted in RAID for rapid access. This will allow us to handle about 40 observations of secondary eclipses in a single-band, which will be sufficient for our complete survey. The same server will be used to perform all data processing; it will be equipped with multiple processors and sufficiently memory to complete the entire analysis of each data-set within a matter of hours. All data products (i.e., not the raw data, which are permanently kept at the CFHT) will be backed up regularly on a dedicated smaller server.

All the data, including the results of our analysis, will be readily accessible to all members of our team through a secure access to our main server. To keep the team informed on the latest progress, we will maintain a log of the observations and a status of the data analysis on a password-protected webpage.

Models. To assist in our understanding of this data we have developed numerical, hot Jupiter atmosphere models. In these numerical models we model the atmospheric pressure-temperature (P-T) profile, chemical abundances, and emergent spectra with a 1D plane-parallel model atmosphere code that has been widely used for exoplanets, as well as brown dwarfs and solar system planets. The code was originally developed for McKay et al. (1989) for the study of Titan’s atmosphere, and has been modified to model Uranus (Marley & McKay 1999), brown dwarfs (Marley et al. 1996, 2002), and highly irradiated exoplanets (Fortney et al. 2005, 2006, 2008). We currently possess coupled chemistry-opacity databases for metallicities from solar, to 3X solar (Jupiter-like), up to 50X solar (Neptune-like). We generally compute self-consistent dayside P-T profiles in radiative equilibrium, but we can also compute spectra from ad-hoc P-T profiles when needed, to yield better fits to observations.

\[3\text{http://www.cfht.hawaii.edu/Instruments/Imaging/WIRCam/\textit{IwiVersion1Doc.html}}\]