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DETECTION AND CHARACTERIZATION OF EXOPLANETS AND BROWN DWARFS: A WHITE PAPER FOR THE 2010 CANADIAN LONG RANGE PLAN

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Subject headings:

1. INTRODUCTION

With the announcements of the first extrasolar planet (51 Peg b) and the first brown dwarfs (Gliese 299b, Teide 1, PPl 15) in 1995, the field of sub-stellar astrophysics entered an unprecedented era of discovery. Since then, over 400 exoplanets , including many in multiple planet systems, as well as hundreds of brown dwarfs, both in the field and in young clusters, have been identified.

These discoveries have provided a definitive answer to the age-old question of whether there are worlds beyond the solar system and partial answers to questions regarding their frequency, diversity and origin. But they have also revealed many surprises that challenge our preconceptions: e.g., giant planets very close (<0.05 AU) to their host stars and very far out (>60-100 AU), highly eccentric orbits, a new class of (rocky?) "super-Earths", and free-floating 'planetary-mass' brown dwarfs. We are now poised to address even more compelling questions regarding the true diversity of sub-stellar worlds, including the frequency of Earth-like and/or habitable planets and the lowest-mass objects that can form in a 'star-like' fashion in isolation or as companions.

2. EXOPLANETS

2.1. *Radial Velocity Surveys: Case for the Infrared*

The majority of exoplanet detections to date involve the radial velocity (RV) method. The precision of the RV technique, pioneered by Campbell, Walker & Yang (1988), has now reached ∼1 m/s, thus making it possible to detect super-Earths (e.g., Mayor et al 2009).

Young stars, however, are much less accessible to precise RV measurements, because such stars are often accreting, or have active magnetic cycles, which influence the line profiles. As a result, the velocity one measures – that of the centre of light – does not accurately trace the centre of mass. Indeed, these effects have been seen in a large survey for binary stars undertaken with MIKE on Magellen (Duy Nguyen's PhD thesis at UofT). Yet, RV surveys of young stars could provide valuable constraints on planet formation and migration scenarios and timescales. Several tactics may help overcome the challenges posed by stellar activity. First, one could measure in the infrared rather than the optical, where at least the systematic effects due to star spots should be much diminished (this expectation is backed up by experiments done by others). Second, by careful analysis of the line shapes on a line-by-line basis, one should be able to use the different temperature sensitivities of different lines to correct for the systematic effects. Third, one can simply observe much more frequently to beat down the noise, on timescales longer than the variability time scale (of order the star's rotational period). Here, the first and second tactics would require high-resolution infrared spectra with large wavelength coverage (echelle), while the third would be best served with a large field-of-view, multi-fiber, preferably infrared spectrograph, with which many young stars could be observed simultaneously.

Going to the infrared could also help find low-mass, rocky planets even around older but active M dwarfs. Recently, Bean et al. (2010) have demonstrated ∼5 m/s long-term precision on M dwarfs with CRIRES on the VLT with an ammonia cell for calibration. A stable infrared echelle spectrograph with broad wavelength coverage per setting could bring significant improvements.

2.2. *Transiting Planets: Characterization Prospects*

Of the growing population of 'hot Jupiters', those caught in transit are well suited for detailed characterization. For example, nearly continuous photometric monitoring with the Canadian MOST ((Microvariablity and Oscillations of Stars) satellite has provided sensitive limits on giant planet albedos (e.g., Rowe et al. 2008) and placed limits on the presence of 'hot super-Earths' (e.g., Croll et al. 2007) in a few systems.

During a transit, some of the starlight passes through the planet's atmospheric limb before reaching us. With extremely precise observations, it is possible to detect absorption features due to the planetary atmosphere in the stellar spectrum. So far, there are successful detections for a few exo-planets (e.g., Redfield et al. 2008).

Some hot Jupiters also pass *behind* their star during the course of an orbit. Infrared observations of these secondary eclipses reveal thermal emission from the (tidally locked) planets' (permanent) dayside. Such measurements have succeeded in the past few years, first with Spitzer and HST and later with ground-based telescopes. Croll et al. (2010) have used CFHT/WIRCam in an optimized mode to detect hot Jupiter secondary eclipses in the near-infrared, at or near the planets' blackbody peaks. These JHK measurements are the most precise yet from the ground. The results suggest a remarkable diversity of atmospheric characteristics among these worlds. Given the large field-of-view and on-chip guiding

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of WIRCam, as well as the already-demonstrated high photometric precision, CFHT is well positioned to play an important role at the forefront of exoplanet research for the next few years. It fills a particularly interesting 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. In the most favorable cases, it may even be possible to measure thermal phase curves of exoplanets with CFHT, as has been done with Spitzer. A cross-dispersed infrared spectrograph could allow the detection of molecules such as methane from the ground (Swain et al. 2010), while JWST and TMT will help extend characterization prospects to 'super-Earth' planets.

2.3. *Direct Imaging: Ready for a Revolution*

Direct imaging (DI) has two major advantages: (a) it is efficient for detecting planets at > 5 AU, (b) atmospheres of directly imaged planets can be studied relatively easily through multi-band photometry or spectroscopy. Thus, DI will help complete the inventory of giant planets at all orbital separations and as a function of stellar age, determine their effective temperature and surface gravity, and probe atmospheric composition, structure and dynamics. In turn, these results will allow us to calibrate atmosphere and evolutionary models and advance our understanding of planet formation, migration and dynamical evolution.

DI is still it its infancy. Yet, adaptive optics (AO) systems on 8-m telescopes, combined with advances in optimal acquisition and data processing strategies, have led to major breakthroughs recently. Canadian astronomers led two of the first three discoveries –the 3-planet system HR 8799 bcd (Marois et al. 2008) and the very young, wide-orbit planet 1RXS1609-2104 b (Lafrenière et al. 2008)– and were involved in the third –the debris-disk planet Fomalhaut b (Kalas et al. 2008). Canadians have also acquired world-class expertise in DI instrumentation and techniques: their contributions include developing TRIDENT camera for CFHT (see WPs from Moon et al. & Bastien et al.) and the Altair AO system on Gemini North (see WP from Véran et al.), pioneering angular and spectral differential imaging techniques and leading large surveys (e.g., GDPS - Lafrenière et al. 2007).

In the next decade, the Gemini Planet Imager (GPI) and the Spectro-Polarimetric High-contrast Exoplanet Research (SPHERE) on the ESO VLT as well as two new observatories, the JWST and the TMT, are expected to revolutionize the DI field. GPI, scheduled to begin operation at Gemini South in 2011, is equipped with a high-order AO system and a coronagraph, an interferometer to measure precisely the residual wave front aberrations and a NIR integral field spectrograph for spectral characterization. It is expected to gain two orders of magnitude in sensitivity compared to current instruments. Young (< 300 Myr) planets down to 1 $M_{Jupiter}$ will be detectable >5 AU around nearby (<100 pc) stars. JWST (scheduled launch 2014) will enable high-contrast, high-resolution imaging and spectroscopy in the mid-infrared, thus complementing ground-based facilities. Mid-infrared is essential to study non-equilibrium chemistry in planetary atmospheres, to measure the strength of water bands in their spectra (impossible from the ground), and to search for satellite debris disks around planets. JWST will also search for planets around fainter and/or redder primaries, which are not suitable for ground-based extreme AO systems. The TMT will provide a remarkable increase in both angular resolution and contrast, compared to today's biggest telescopes, and open up a new discovery space. The TMT NFIRAOS facility AO system (being designed at HIA, see Véran et al. WP) will achieve high astrometric precision for orbit determination and high spectral resolution for atmosphere characterization. When equipped with an optimized instrument, it will be able to search for giant planets down to 1-2 AU, to detect Neptune-like planets, and possibly to image rocky planets in the habitable zones of nearby stars. In addition, both the TMT and the Canadian-built instrument onboard JWST - the tunable filter imager, using non-redundant masking interferometry - will enable the detection of newborn planets in nearby star-forming regions.

Space-based telescopes optimized for high contrast imaging will be required for DI and spectroscopy of Earth-like planets. Several mission concepts are under study, including PECO, Eclipse and TPF-C, but currently do not have significant Canadian involvement.

3. BROWN DWARFS

3.1. *Young BDs: Tracing the Low End of the IMF*

Growing evidence suggests that most BDs likely form in a star-like manner and go through a T Tauri phase, accompanied by accretion disks (e.g., Jayawardhana et al. 2003a, 2003b, Mohanty et al. 2005; Scholz et al. 2006) and outflows. Meanwhile, deep surveys of a few young star clusters have revealed free-floating objects with estimated masses not much higher than those of giant planets (e.g., Zapatero Osorio et al. 2000). In other words, the stellar initial mass function (IMF) appears to extend well into the 'planetary' mass regime. Surveys to date have not answered decisively two of the most fundamental questions about them: (1) What is the lower limit for the mass of objects that form like stars? (2) How common are PMOs relative to low mass stars and BDs?

The on-going SONYC (Substellar Objects in Nearby Young Clusters) project aims to address these questions by conducting optical and near-infrared surveys of nearby star-forming regions to unprecendented depth, with follow-up spectroscopy for candidate confirmation. In NGC 1333, for example, the SONYC team find an overabundance of BDs relative to low-mass stars (by a factor of 2-5) but also a deficit of PMOs (Scholz et al. 2009). By characterizing the low end of the IMF in several star-forming regions down to a few Jupiter masses –i.e., the lowest mass limit for fragmentation predicted by a variety of theoretical calculations– it will be possible to look for environmental differences. The resulting PMO samples will also be useful for constraining atmosphere and evolutionary models for giant planets. The lack of Canadian access to wide-filed optical+infrared imagers and multi-object infrared spectrographs on 8m telescopes has hampered the efforts to date; so far, the SONYC project has relied on limited access to Subaru and VLT through international collaborators. The planetary mass candidates are often too faint for spectroscopy even with 8m telescopes, and will require JWST and TMT.

Studies of BD binaries could distinguish between formation scenarios and help calibrate evolutionary models. Laser guide star AO on 8m telescopes is often essential for resolving tight BD binaries, JWST and TMT are required for imaging the lowest-mass/coolest binaries.

3.2. *Field BDs: Probing Cool Atmospheres*

The spectroscopic sequence that BDs go through, as they cool over Gyr, has been modeled with reasonable success. Early on, metal hydrides and oxides such as TiO and VO in gaseous form dominate BD spectra (M dwarfs). Later, these volatiles condense into grains, changing the emerging spectral energy distribution dramatically (L dwarfs). Grains ultimately sink below the photosphere leaving only a handful of chemical species such as CH_4, H_2O, H_2, CO and, for the coolest objects, NH_3 (T and Y dwarfs). Two areas of field BD study are especially noteworthy: the L/T spectral type transition and cooler end of the temperature range.

The L/T transition is marked by rapid evolution of near-infrared colors at ∼1400 and brightening of J-band (1.2μm) flux. Disappearance of dust clouds below the photosphere probably account for these changes, but current 1D models fail to reproduce them. If the clouds settle in a non-uniform manner, transition objects may have a mottled appearance, resulting in photometric variability on rotational timescales. Recent photometric monitoring has shown that at least some L/T transition objects display quasi-periodic flux modulations. Telescopes of 1–4m-class (OMM, CFHT, Las Campanas 2.5m) are well suited for variability surveys. Time-resolved spectroscopy on 4 and 8-m telescopes should clarify the nature of the variability. The planned high-resolution infrared spectrographs on 4-m telescopes (e.g., SPIRou at CFHT, CARMENES at Calar Alto) could be used for Doppler imaging of the brightest cool dwarfs.

Cooling models suggest that the oldest BDs in the solar neighborhood would have reached room temperatures. But, given the observational challenge of identifying them, the coolest field BD known until recently is at a temperature of 800 K. Wide-field, deep near-infrared surveys (CFBDS, UKIDSS) are starting to fill the 200-800 K range, the only temperature gap left from solar system giant planets to the hottest stars. Of the ∼10 objects uncovered so far below 800 K, the coolest approaches 500 K. These isolated ultracool brown dwarfs, unencumbered by a parent star's glare, are excellent proxies to test giant planet models. First generation near-infrared surveys (2MASS, DENIS) were performed on 1m telescopes and found BDs down to 800K. Surveys on 4-m telescopes (CFHT, UKIRT) were required to uncover cooler objects; their follow-up challenges the most sensitive near-infrared spectrographs on 8m class telescopes. Characterization the coolest BDs will require JWST in the mid-infrared and TMT for high-resolution near-infrared spectroscopy.

4. THEORETICAL MODELS

While this WP has focused on a few key observational aspects of exoplanets and BDs, these efforts are closely linked to theoretical work on many fronts, including star formation (see WP by Johnstone), circumstellar disks and planet formation (see WP by Kavelaars), planetary system dynamics, and atmosphere and evolutionary models for planets and BDs. For example, observational constraints on the low end of the IMF and BD binaries can help distinguish between sub-stellar formation scenarios; thermal emission measurements and transmission spectroscopy of hot Jupiters advance our understanding of the physics, chemistry and meteorolgy of their atmospheres; mass estimates of directly imaged planets usually depend on evolutionary models.

There is a vigorous community of theorists in Canada working on star and BD formation, disk evolution, and planet formation, migration and dynamics. However, one glaring weakness is the absence of theorists focusing on the atmosphere and evolutionary models of BDs, giant planets and terrestrial planets.

5. RECOMMENDATIONS FOR THE LONG RANGE PLAN

Manpower & Expertise. Hiring postdoctoral researchers remains the biggest hurdle for the sub-stellar research community. Top-notch postdocs, recruited from around the world, are essential to exploit fully the capabilities of upcoming facilities and instruments such as Gemini/GPI, JWST and TMT, especially in campaign mode, but it is extremely difficult to secure sufficient funds. Our community is not alone in finding this perhaps the weakest aspect of the Canadian funding model.

Expertise in atmosphere and evolutionary models of Jovian and terrestrial planets is currently lagging in Canada. Such expertise is required for interpreting current and future discoveries.

Observatories & Instrumentation. The new frontiers in RV planet surveys include searches for rocky planets around nearby stars and newborn planets around young stars. A stable high-resolution infrared spectrograph (with broad wavelength coverage per setting) on a 4m or 8m telescope will help tremendously in both cases. To be competitive, it needs to be operational within a few years. Such an instrument, especially if mounted on a 8m, would also be useful for detection of transiting planet atmospheres and for BD studies (spectroscopic characterization, binarity, rotation, Doppler imaging).

Access to next generation extreme-AO planet imaging instruments on large existing telescopes –namely, GPI on Gemini and/or SPHERE on VLT– for large campaigns and astrometric/spectroscopic follow-up is critical to maintain Canada's position at the forefront of exoplanet imaging. The JWST will be a unique facility for characterizing planets and BDs in the thermal infrared, and for imaging faint sub-stellar companions at close separations. With optimized instruments, the TMT will permit the direct detection of fainter/older planets (possibly down to rocky worlds) as well as newborn planets in nearby star-forming regions. Canadian involvement in a space-based mission for high contrast imaging and spectroscopy, such as TPF-C, for detection and characterization of Earth-like planets, should be considered seriously.

The lack of Canadian access to truly wide-field (i.e., degree-scale) optical+infrared imagers and multi-object spectrographs on 8m-class telescopes remains a concern, e.g., for BD and RV surveys in clusters.

Coordination. A network model similar to the CIAR Cosmology and Gravitation program would provide improved interactions and additional manpower to position the Canadian exoplanet & BD research community at the forefront of this exciting field.

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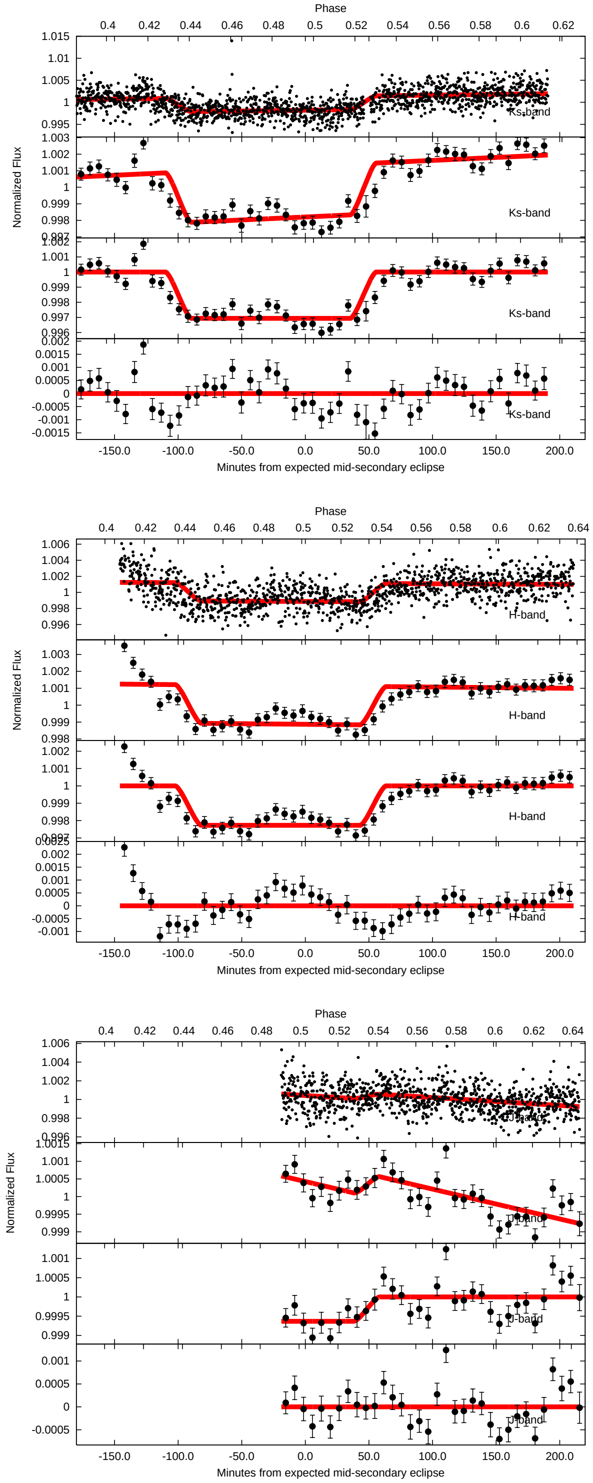

FIG. 1.— Infrared observations of hot Jupiter secondary eclipses measure thermal emission from the (tidally locked) planets' (permanent) dayside. Such measurements have succeeded in the past few years, first with Spitzer and HST and later with ground-based telescopes. This figure shows CFHT/WIRCam photometry of the secondary eclipse of the exoplanet WASP-12b, from UofT PhD student Bryce Croll and collaborators. The Ks, H & J-band observations are taken on different days. In each set the top panel shows the unbinned lightcurve with the best-fit secondary eclipse and background (red line). The second panel shows the lightcurve with the data binned every 10.0 minutes and again the best-fit eclipse and background. The third panel displays binned data after the subtraction of the best-fit background, Bf, along with the best-fit eclipse model. The bottom panel shows the binned residuals from the best-fit model.

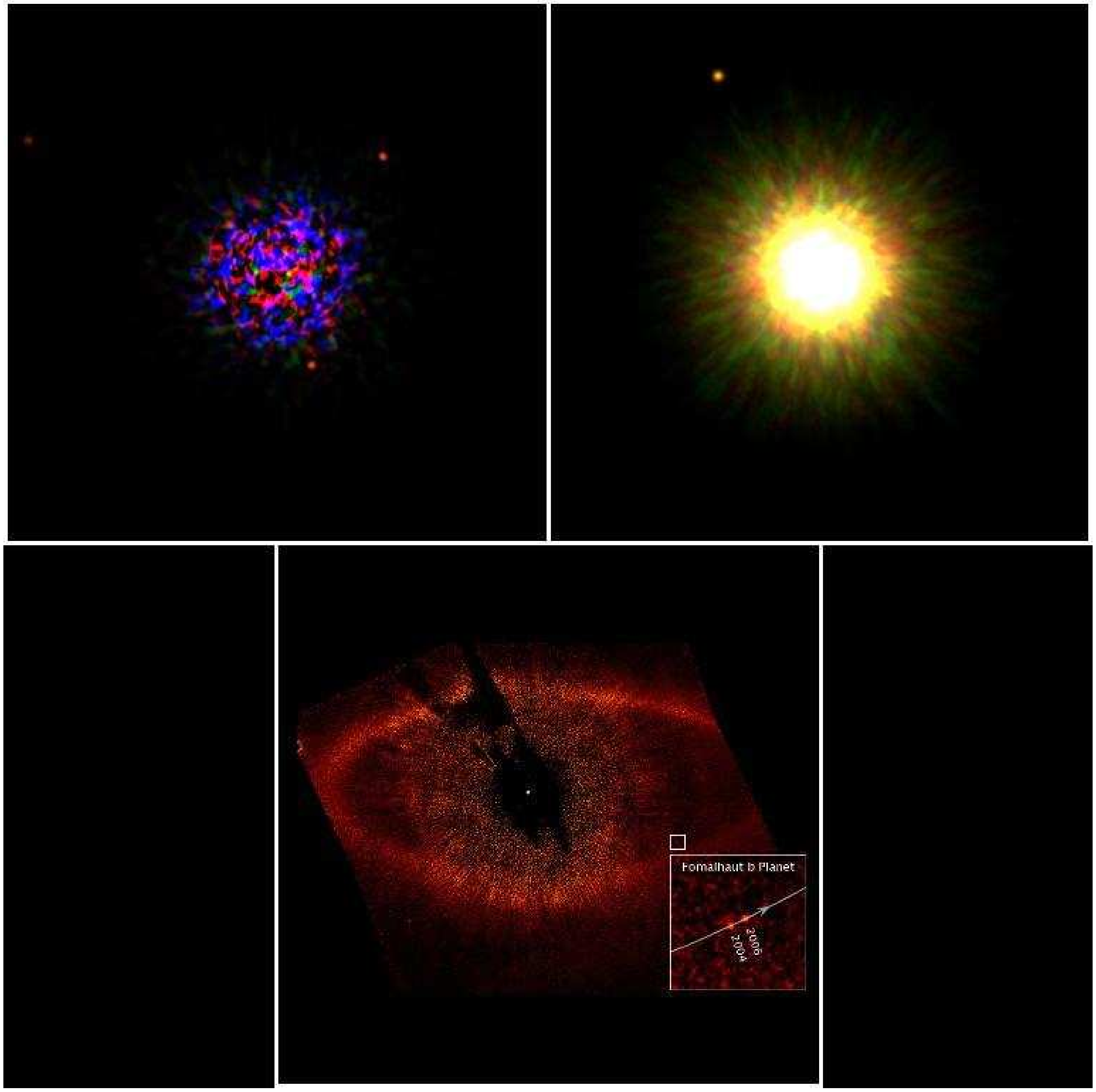

Fig. 2.— In 2008, Canadians were involved in several breakthroughs in exoplanet imaging. Upper left: A deep AO survey of massive young stars resulted in the discovery of the HR 8799 three planet system (Marois et al. 2008). The three 7-10 Jupiter mass planets are in orbits between 24 and 68 AU around the star. Upper right: An extensive AO survey of young stars in the Upper Sco association reveald a 7 Jupiter mass candidate planet 300 AU from to the star 1RSX J160929.1-210524 (Lafrèniere et al. 2008), now with confirmed common proper motion (Lafrèniere, priv. com.). Bottom: A long-integration HST/NICMOS image of Fomalhaut found a <3 Jupiter mass candidate planet 110 AU around the star (Kalas et al. 2008). These three remarkable discoveries are the first steps that will lead in the near future to the discoveries of many less massive/closer-in planets with extreme AO instruments (e.g., Gemini Planet Imager) and the JWST, and to likely direct detection of super-Earths with TMT.

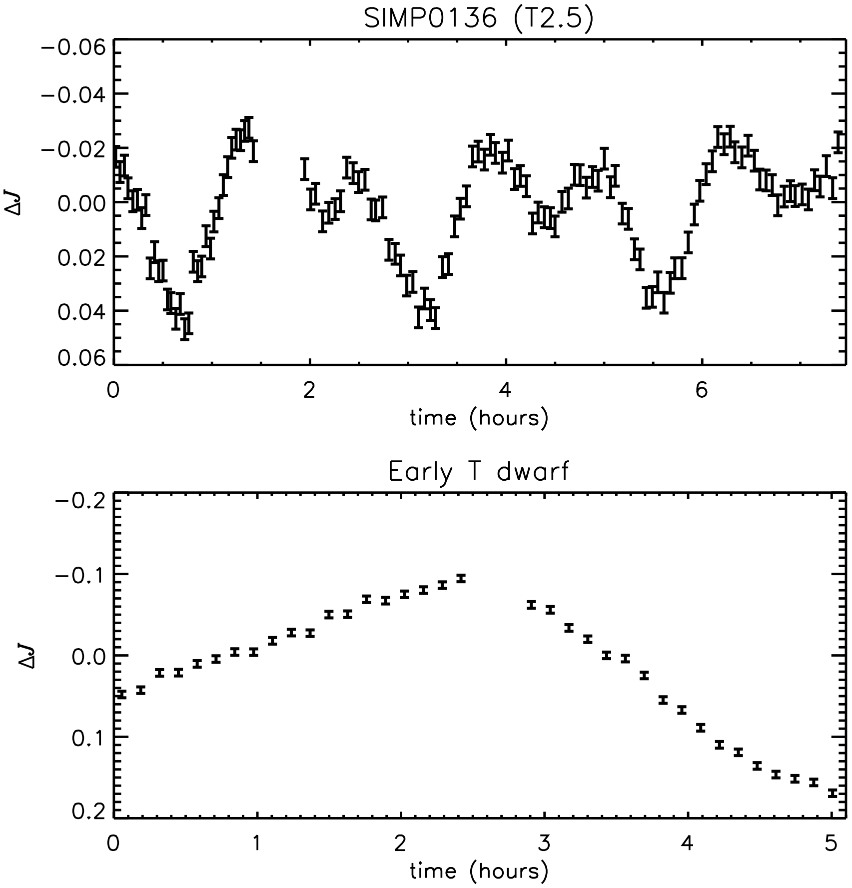

FIG. 3.— Photometric variability is a powerful tool for investigating the L/T transition and weather in brown dwarfs. This figure shows J-band lightcurves of the two most variable field brown dwarfs known to date, both Canadian discoveries. They display quasi-periodic flux modulations on the timescales of hours, presumably related to the rotational periods, as well as significant night-to-night evolution of their lightcurves suggesting that weather patterns that evolve on timescales of a few days. The datasets were obtained at the OMM 1.6-m and Las Campanas 2.5-m telescopes. Top plot is from Artigau et al. (2009), bottom plot from UofT PhD student Jacqueline Radigan and collaborators.

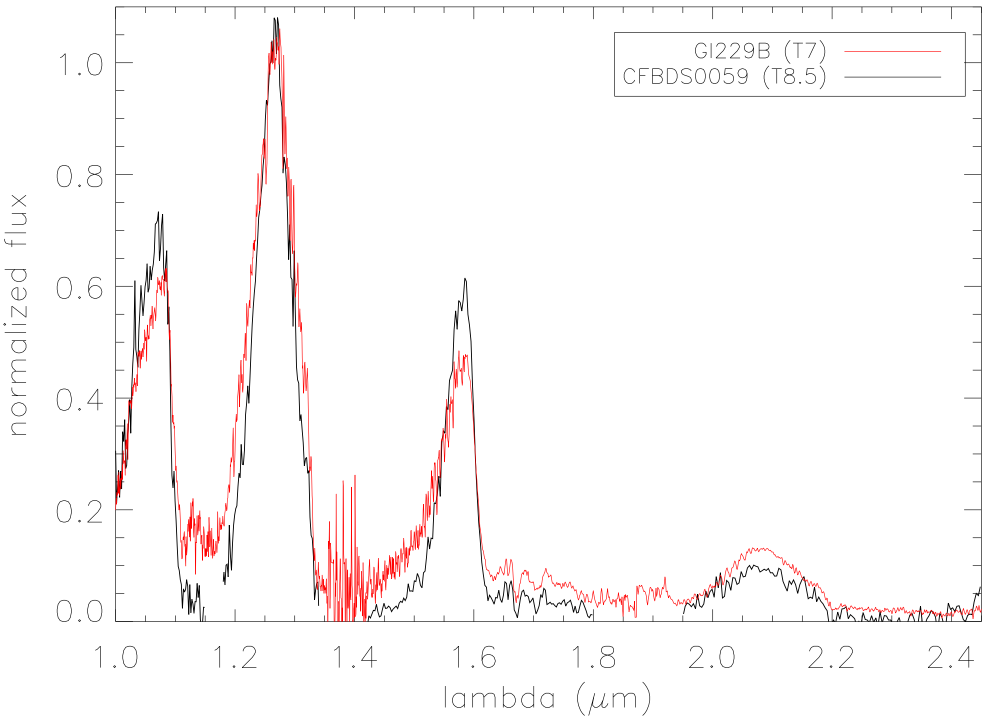

Fig. 4.— Near-infrared spectra of CFBDS0059 and Gl229b. While Gl229b (T=900K) was the first clear-cut brown dwarf discovered in 1995, it remained among the coolest known BDs until recently. CFBDS0059, uncovered by the Canada-France Brown Dwarf Survey (CFBDS; Delorme et al. 2008) has an estimated temperature of 625 K and displays a significantly narrower J-band peak (centred at 1.25μm), signs of stronger water absorption and an even deeper CH_4 band (1.6-1.75μm). Detailed analysis of CFBDS0059 spectrum in the 1.5-1.6μm interval shows the appearance of a new absorber, tentatively identified as NH_3, that was not observed in warmer objects.