Cool Star Science with the FIRE Spectrograph

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Abstract. The Folded-port InfraRed Echellette (FIRE) has recently been commissioned on the Magellan 6.5m Baade Telescope. This single object, near-infrared spectrometer simultaneously covers the 0.85-2.45 $\mu$m window in both cross-dispersed ($\lambda/\Delta\lambda \approx 6000$) or prism-dispersed ($\lambda/\Delta\lambda \approx 250-350$) modes. FIRE’s compact configuration, high transmission optics and high quantum efficiency detector provides considerable sensitivity in the near-infrared, making it an ideal instrument for studies of cool stars and brown dwarfs. Here we present some of the first cool star science results with FIRE based on commissioning and science verification observations, including evidence of clouds in a planetary-mass brown dwarf, accretion and jet emission in the low-mass T Tauri star TW A 30B, radial velocities of T-type brown dwarfs, and near-infrared detection of a debris disk associated with the DAZ white dwarf GALEX 1931+01.

1. The FIRE Spectrograph

In March 2010, the Folded-port InfraRed Echellette (FIRE) was successfully commissioned on the Magellan 6.5m Baade telescope, following three years of design, development and construction at MIT and the University of Rochester. FIRE is a single-object,
near-infrared spectrometer designed to cover the entire 0.85-2.45 $\mu$m window in a single exposure, at a resolution optimizing the balance between telluric OH absorption avoidance and sensitivity for faint near-infrared sources. Its primary cross-dispersed mode delivers moderate-resolution spectra, $\lambda/\Delta\lambda \approx 6000$ (for the 0.6' or 4-pixel wide slit), across 21 orders, simultaneously imaged onto a single HAWAII-2RG detector. A prism-dispersed mode (echelle grating replaced with a mirror) delivers low-resolution spectra, $\lambda/\Delta\lambda \approx 250-350$ (varying across the detector), at higher throughput. Preliminary zeropoints (1 count/second/pixel) for these two modes are AB $\approx 17$ and AB $\approx 20-21$, respectively, based on observations of the near-infrared spectrophotometric flux standard GD 71 (Figure 1). These correspond to 1 hr limiting magnitudes for signal-to-noise $S/N \approx 5$ of $\sim 21$ and $\sim 23-24$, respectively (note the higher background penalty at low resolution). A second near-infrared camera images the entrance slit through an MKO $J$-band filter for source acquisition and manual guiding, and can easily acquire sources with $J = 19–20$ (AB) in 20–30 s exposures. An external calibration unit is mounted to the spectrograph, with a fold mirror used to direct quartz flat field and ThAr lamp light into the instrument for calibration of the cross-dispersed mode (calibration of the prism-dispersed mode is done using lamps reflected off of the Baade dome spot). The entire instrument is compact (~1 m across) and mounted on one of three f/11 auxiliary (folded) ports along the mirror support structure (Figure 1). FIRE is continuously available and directed on-sky using a tertiary fold mirror in the telescope, allowing for target-of-opportunity observations and integration with other Baade instruments (e.g., the forthcoming FourStar imager; Persson et al. 2008). A data reduction pipeline based on MASE (Bochanski et al. 2009) is nearing completion and is expected to be delivered in early 2011. Further details on FIRE’s design and construction can be found in Simcoe et al. (2008, 2010) and on the instrument webpage, http://www.firespectrograph.org.
2. Early Cool Star Science with FIRE

2.1. Clouds in Planetary-Mass Brown Dwarfs

FIRE’s prism-dispersed mode allows single-order measurement of the near-infrared spectral energy distributions of faint brown dwarfs, including L- and T-type dwarfs, with resolution sufficient to study molecular band and atomic line features, and broadband spectral structure. The latter is relevant to the study of mineral condensate clouds present in the cool photospheres of these sources (e.g., Lunine et al. 1989; Tsuji et al. 1996; Helling et al. 2001). Condensate grains reveal themselves in the near-infrared by modulating broadband spectral color and H\textsubscript{2}O band absorption. The influence of clouds on emergent spectra is prominent for the warmer L-type dwarfs (e.g., Baraffe et al. 1998; Marley et al. 2002), but clouds are presumed to have sunk below the photospheres of T dwarfs cooler than \(\sim 1000\) K (Ackerman & Marley 2001; Burrows et al. 2006). Our early results with FIRE suggest that young T dwarfs may in fact have significant cloud opacity at their photospheres.

![Figure 2. FIRE spectroscopy of the T8 dwarf Ross 458C (black line) compared to best-fit models from Saumon & Marley (2008) with (blue line) and without (red line) cloud opacity. The cloudy model more accurately reproduces the relative \(J\)– to \(H\)–band peak fluxes, the result of increased opacity at the shorter wavelength peak. The inferred effective temperature from the model fits, \(T_{\text{eff}} = 635^{+25}_{-35}\) K, is consistent with estimates based on the luminosity and age of the source.](image)

During our March 2010 commissioning run, we obtained prism spectra of the brown dwarf candidate Ross 458C (Scholz 2010; Goldman et al. 2010), a widely-separated (102\arcsec), common proper motion companion to the nearby M0.5Ve + M7 Ross 458 binary. Due to the high throughput of FIRE’s prism mode, exposures were limited to
150 s to avoid saturating telluric OH lines in the $H$-band region\textsuperscript{1}, although only four exposures (10 min total integration) were needed to obtain $S/N \approx 50$-80 in the $Y JHK$ flux peaks for this $J = 16.7$ source (Figure 2). The observations identify Ross 458C as a T8 dwarf, and provide sufficient resolution to measure its weak 1.25 $\mu$m K I doublet lines. The inferred classification and known distance of Ross 458C permit an estimate of its bolometric luminosity, while the 150–800 Myr age of the system as inferred from the active, rapidly-rotating primary further indicate a low effective temperature ($T_{\text{eff}} = 650 \pm 25$ K) and low mass ($M = 6$–11 $M_{\text{Jup}}$) for this source. With a projected separation of 1100 AU, Ross 458C is the most widely-separated planetary-mass companion to a nearby star identified to date (Burgasser et al. 2010b).

The FIRE spectrum of Ross 458C was compared to atmospheric models from Saumon & Marley (2008), with separate comparisons made to models with and without cloud opacity. We found that cloudy models provide significantly better fits to the spectrum than the cloud-free models, more accurately reproducing the relative $J$- and $H$-band peak fluxes. This is the first spectroscopic evidence of clouds in the photosphere of a low-temperature brown dwarf and in a planetary-mass object. However, Ross 458C may be a special case, as its youth and supersolar metallicity (also inferred from the properties of its primary) may result in higher clouds with larger grains (more opacity) and possibly more condensate material. Similar arguments have been proposed to explain the apparently thick clouds of young, low-gravity L dwarfs (Metchev & Hillenbrand 2006; Cushing et al. 2008).

2.2. Accretion and Jet Emission in a Low-mass T Tauri Star

![Figure 3](image_url)

Figure 3. Accretion signatures in the spectrum of the low-mass TW Hydrae object TWA 30B: 0.985 $\mu$m [C I] (left) and 1.083 $\mu$m He I (right). The [C I] line traces collisionally excited gas in the inner regions of the disk, and compared to mid-infrared [C I] emission can provide a measure of the size of the gaseous disk. The He I line is heavily broadened, evidence of ongoing accretion from an edge-on disk.

\textsuperscript{1}Subsequent observations suggest that prism exposures should be limited to 120 s in typical observing conditions to avoid nonlinearity in the OH region.
Actively accreting low-mass stars exhibit a broad range of emission features arising from inflow onto the central star, jets and disk/star interactions via magnetic fields (e.g., Küker et al. 2003; Whelan et al. 2007). Many of these emission diagnostics are found at near-infrared wavelengths, including line and molecular band emission (e.g., Najita et al. 2003; Fischer et al. 2008). We used the moderate-resolution mode of FIRE to search for these diagnostics in the occluded low-mass T Tauri star TWA 30B (Looper et al. 2010; see poster by D. Looper). This M4 dwarf exhibits several indicators of an edge-on, actively accreting disk, including strong H I and alkali emission, forbidden line emission (tracing jet outflows), variable infrared excess, and an overall obscuration of at least 5 mag in the $K$-band relative to its M5 common proper motion companion TWA 30A. Among the emission lines detected in the optical spectrum of TWA 30B were the 0.873 $\mu$m and 0.985 $\mu$m transitions of [C I], lines previously detected in planetary nebulae (e.g., Jewitt et al. 1983) and cometary comae (e.g., Oliversen et al. 2002), but not (to our knowledge) in the spectrum of a T Tauri star. Figure 3 shows a close-up of the FIRE cross-dispersed spectrum of this source obtained on 3 April 2010 (UT); the [C I] line is clearly present with an equivalent width of $\sim$12 Å. In addition, we detected the 1.083 $\mu$m He I line, broadened to a full width half maximum of $\approx$100 km s$^{-1}$. He I emission had not been seen in the optical spectrum of this source. The high-excitation [C I] line, formed in the inner regions of the disk, is an important tracer of gasous disk size when compared to the fine structure, mid-infrared [C I] lines formed in the colder outer regions of the disk (Ercolano et al. 2009). He I emission directly measures accretion, and the unexpected appearance of this line in the FIRE data suggests episodic accretion or variable obscuration is taking place on TWA 30B.

2.3. Identification and Kinematics of the Coldest Brown Dwarfs

FIRE is ideal for confirmation and kinematic studies of cold, intrinsically faint brown dwarfs. The prism mode is particularly useful for following up new discoveries anticipated from the Wide-field Infrared Survey Explorer (WISE; e.g., Liu et al. 2008) and the Visible and Infrared Survey Telescope for Astronomy (VISTA; Emerson et al. 2004). During commissioning observations, several promising WISE cold brown dwarf candidates were targeted for observation (see contribution by J. D. Kirkpatrick).

The cross-dispersed mode is also useful for extending 3D kinematic studies of “ultraceool” low mass stars and brown dwarfs (e.g., Zapatero Osorio et al. 2007; Schmidt et al. 2010) down to the “ultracold” regime (i.e., $T_{\text{eff}} < 800$ K). As an example, Figure 4 displays cross-dispersed observations of the $T_{\text{eff}} \approx 500$ K UGPS J072227.51-054031.2 (hereafter UGPS J0722-05; Lucas et al. 2010). With $J = 16.5$, UGPS J0722-05 is too faint for high-resolution spectrographs such as Keck/NIRSPEC (McLean et al. 2000), but is an easy target with FIRE. The forest of molecular lines from H$_2$O and CH$_4$ in the near-infrared can be exploited to yield radial velocities accurate to $\lesssim 5$ km s$^{-1}$ through cross-correlation techniques (the native resolution of the data shown in Figure 4 is 50 km s$^{-1}$). We are currently conducting a radial velocity survey of $\sim$70 late-type L and T dwarfs within 20 pc of the Sun, and have obtained multi-epoch spectra for a handful of unresolved L/T binary candidates that are potential radial velocity variables (e.g., Burgasser et al. 2008; Blake et al. 2008; Burgasser et al. 2010a).

2.4. Terrestrial Planet Accretion onto a White Dwarf

The unusually metal-rich spectra of DAZ white dwarfs are attributed to the accretion of metal-rich material, potentially from remnant planetary bodies (e.g., Zuckerman et al. 2008).
Figure 4. Cross-dispersed spectrum of the $J = 16.5$, $T_{\text{eff}} = 500$ K T10 brown dwarf UGPS J0722-05, based on a preliminary FIRE data reduction pipeline. Much of the “noise” in these data arise from molecular transitions of H$_2$O and CH$_4$ that blanket the near-infrared spectra of cold brown dwarfs (Bochanski et al., in prep.).

Excess infrared emission associated with these stars can also be interpreted as arising from an accretion disk or a low-temperature companion (e.g., Debes et al. 2005; Jura et al. 2007). A recent case in point is GALEX J193156.8+011745, a heavily polluted DAZ with exceptional abundances of heavy elements and near-infrared excess. Vennes et al. (2010) attributed these features to the presence of an mid-type L dwarf companion polluting the white dwarf through Roche lobe overflow.

We observed GALEX 1931+01 with FIRE, using both the cross- and prism-dispersed modes. As shown in Figure 5, these data confirm the near-infrared excess inferred from photometric measurements, but reveal no spectral features indicative of an L or T dwarf companion. Rather, the spectrum indicates the presence of a hot dust disk (i.e., a “ring of fire”), the remains of tidally-disrupted, terrestrial-like planetary body (Melis et al., submitted).

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Figure 5. Prism-dispersed FIRE spectrum of the DAZ GALEX 1931+01. The observed spectral energy distribution (red line) deviates from the $T_{\text{eff}} = 23,500$ K, $\log g = 8.0$ (cgs) atmosphere model (blue dotted line) in a manner consistent with the presence of flat, opaque dust disk (blue dashed line). The green dot-dashed line shows the sum of the atmosphere and disk models (Melis et al., submitted).

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FIRE Sensitivity [PRELIMINARY]

Echelle mode
Standard: GD71, 300 sec
UT 6 April 2010
Slit: 0.6, seeing: 0.6
Airmass: 1.74 (no correction)
No correction for telescope, slit losses
No correction for telluric absorption

Includes slit, telescope losses