Diagnostic Filters for Exoplanets and Brown Dwarfs from 1-5 μm

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Introduction

JWST is being designed to directly detect and characterize extrasolar giant planets in the solar neighborhood. To this end, we have undertaken an effort to define a set of 1-5 μm filters for the NIRCam instrument on JWST that are diagnostic of temperature and surface gravity for brown dwarfs and exoplanets over a wide range of masses and ages. While the discovery of such objects is on-going, surveys are being undertaken to characterize their frequency and physical properties. In this context, the optimum design of such diagnostic filters Is important for efficiently characterizing the nature of objects with known distance as well as identifying foreground/background objects in cluster studies.

The Input Models

The theoretical spectra examined in this study have been taken from Burrows, Sudarsky, & Lunine (2003, ApJ, 596, 587; hereafter BSL2003). They have produced ~0.4-30 μm equilibrium models for a set of 32 isolated objects with masses from 1 – 25 $M_{jupiter}$ and ages from 100 Myr – 5 Gyr (corresponding to temperatures from ~130 – 860 K and $Log_{10}[gravity[cm/s^2]]$ from 3.2-4.9). See figure 1 for some sample spectra.

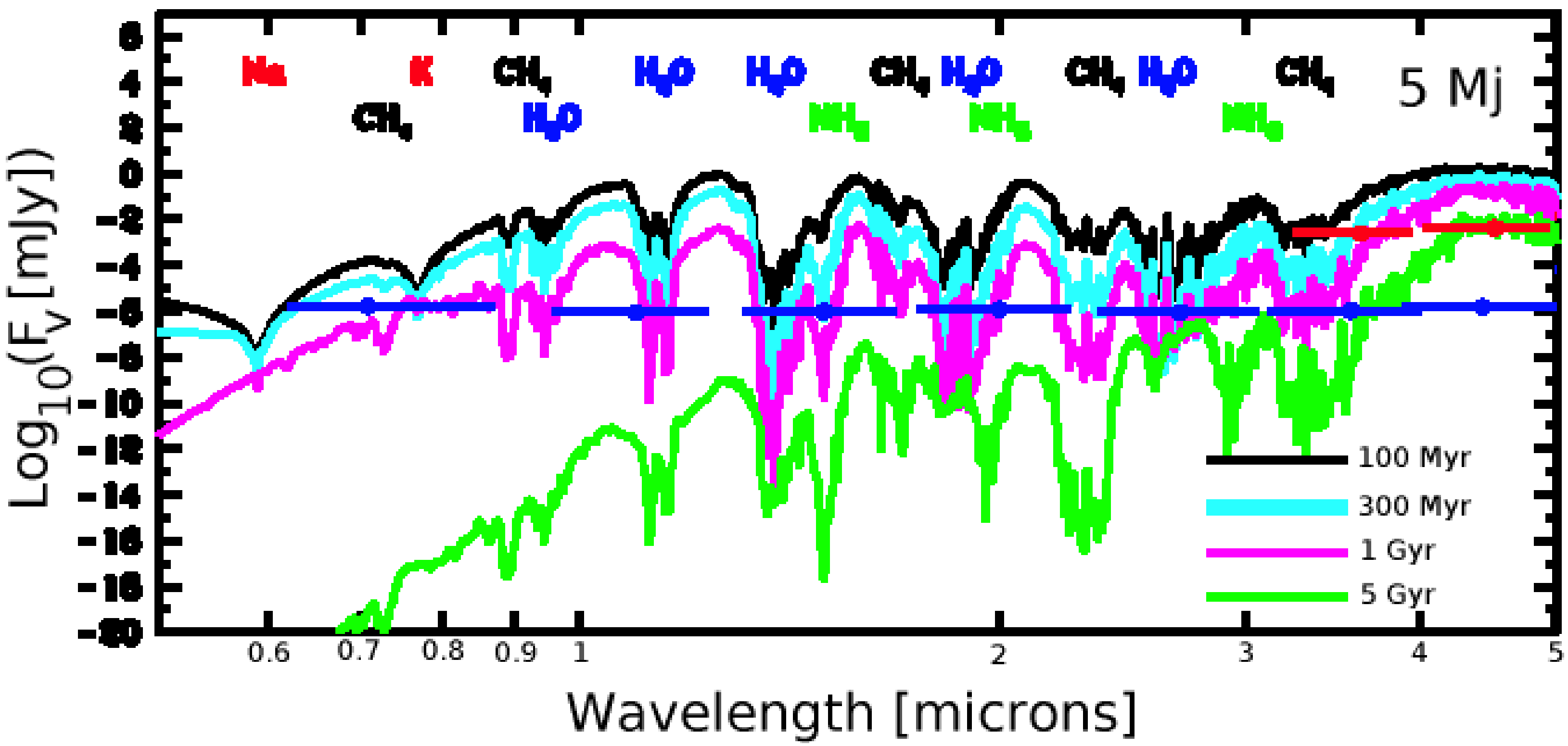

Figure 1. 5 $M_{jupiter}$ spectra at various ages from BSL2003.

Flux Calculation and Errors

Flux values were calculated for every modelled object for a set of filters with central wavelengths from 1 – 5 μm sampled every 0.05 μm and widths from 0.02 – 1.2 μm sampled every 0.02 μm. The filters are approximated by boxcars with 85% transmission in band and 0% transmission out of band. Errors in these fluxes are calculated using estimated NIRCam sensitivities (M. Rieke et al. 2003, Proc. SPIE, 4850,478). Errors in colors, below, conservatively include absolute calibration errors (Campins et al. (1985)).

Choosing Temperature and Gravity Indicators

To narrow down the list of potential temperature indicators, a temperature vs. color plot was created for every possible color from the set of fluxes calculated. A linear fit was then applied and all colors with linear fits that had $\chi^2<100000$ and slope>100 K/mag were considered further. These cuts were determined by an inspection of typical linear fits by eye. The remaining plots were inspected visually for the 3 "best" looking relationships. There was no consideration of the flux errors and color combinations were restricted to two filters of the *same* width. Only widths of 0.02, 0.04, 0.06, 0.08, 0.1, 0.2, 0.3, 0.4 μm were examined. The same process was applied to determine a set of gravity indicators. This time, two cuts were made in color: $\chi^2<4$ slope>1 log g[cm/s^2]/mag and $\chi^2<2$ slope>0.1 log g[cm/s^2]/mag. The four "best" plots were kept. In addition, two gravity indicators were picked out by eye from the whole, uncut, set of plots. See Figure 2 for an example of temperature and gravity indicators that were kept.

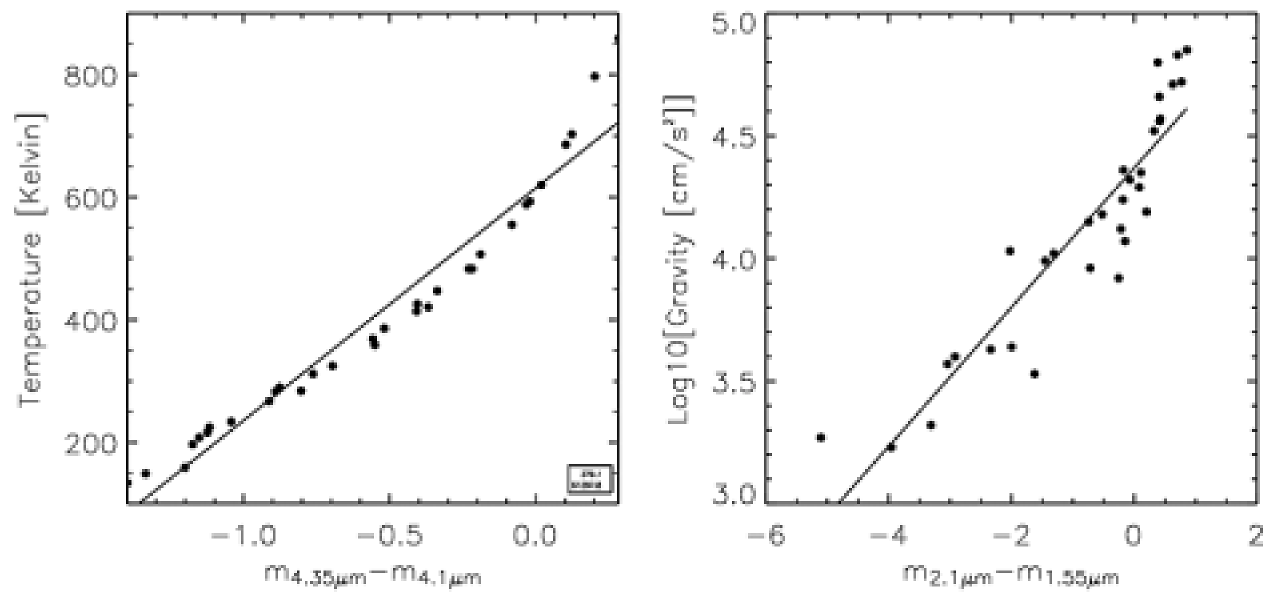

Figure 2. (left) example temperature indicator χ^2=61300 slope=379 K/mag (right) example gravity indicator χ^2=1.1 slope=0.3 log[cm/s^2]/mag

Choosing the Optimal Color/Color Diagram(s)

The above analysis resulted in 18 color/color diagrams. To decide between these, two surface plots were created for each color/color diagram (one with Temperature for the z axis and the other with Gravity as the z axis; see Figure 3 for an example). These surface plots were created by performing a polynomial surface fit to the data of order 2 x 2 (a fit order of 2 x 2 was chosen because it showed a natural break point in a plot of fit RMS residuals vs. fit order).

The two polynomial fits for each color/color diagram resulted in two equations for calculating temperature and gravity of an object given the two specified colors. Errors in the derived temperature and gravity were determined by propogating the errors in the colors (determined previously) through the fit. The median and average error of all 32 modelled objects were used as “figures of merit” in determining which color/color diagram(s) was best. Figure 4 shows the adopted diagrams.

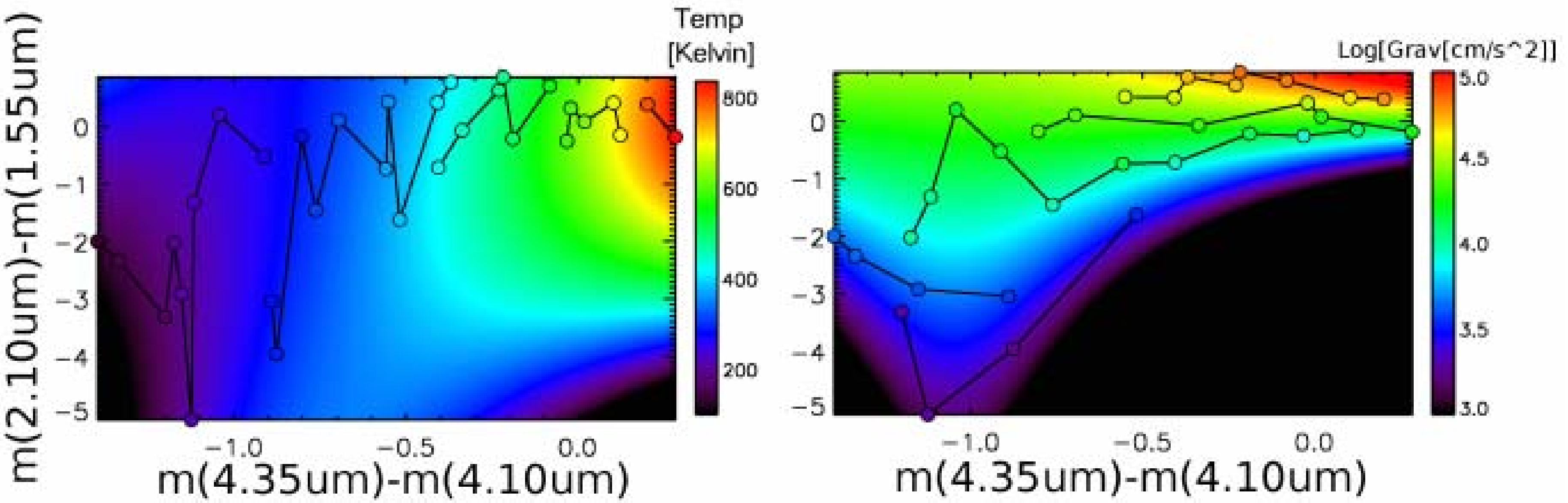

Figure 3. A color/color diagram where the z axis is color coded by temperature for the left and gravity for the right. The colors inside of the data points indicate what the model temp/grav is for that particular object. The background color coding shows the polynomial fit to the data. A good match of the fit to the data is indicated when the color inside of a data point matches the color immediately surrounding that data point. Data points on the left are connected by similar temperature and data points on the right are connected by similar gravities.

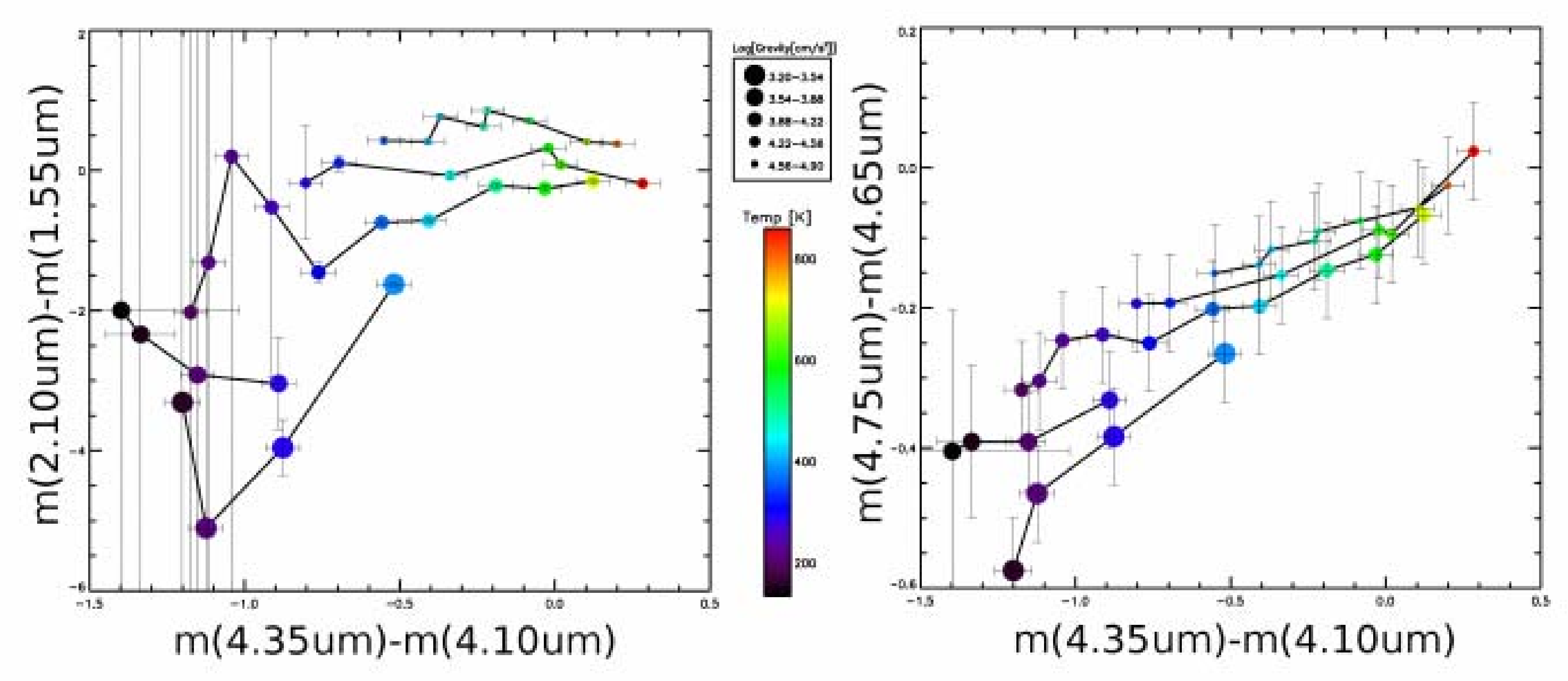

Figure 4. Color/color diagrams derived for each of the 32 models with errors in the colors as described earlier. These errors are for a 2 hr exposure on NIRCam with the objects placed at 10pc. Similar gravities are connected. The left plot has a median/mean temperature error of 32.9/3.7x10^{10} Kelvin and a median/mean log(gravity[cm/s^2]) error of 0.05/2.7x10^8. This plot was optimized for younger, higher mass objects, for which it gives smaller errors. The right plot has a median/mean temperature error of 32.8/33.9 Kelvin and a median/mean log(gravity[cm/s^2]) error of 0.66/0.57. This plot was chosen to be optimized for older, lower mass objects.

Results

Based on the BSL2003 models at a distance of 10 pc, a color/color diagram with $m(\lambda_c=4.35\mu m,\Delta\lambda=0.40\ \mu m)-m(\lambda_c=4.1\mu m,\Delta\lambda=0.40\ \mu m)$ and $m(\lambda_c=1.55\mu m,\Delta\lambda=0.02\ \mu m)-m(\lambda_c=2.1\mu m,\Delta\lambda=0.02\ \mu m)$ can estimate temperatures within ~50 K and log g[cm/s^2] within ~0.6 for EGPs/BDs between 1-10 $M_{jupiter}$ at 100 Myr and 10-25 $M_{jupiter}$ at 5 Gyr. For a color/color diagram with $m(\lambda_c=4.35\mu m,\Delta\lambda=0.40\ \mu m)-m(\lambda_c=4.10\mu m,\Delta\lambda=0.40\ \mu m)$ and $m(\lambda_c=4.65\mu m,\Delta\lambda=0.08\ \mu m)-m(\lambda_c=4.75\mu m,\Delta\lambda=0.08\ \mu m)$, temperatures can be estimated within ~150 K and log g[cm/s] within ~0.9 for all modelled objects. Thus with 4 filters, NIRCam should be able to usefully diagnose temperature and gravity and hence characterize EGP/BDs around nearby stars.