Studying exo-planetary Atmospheres: from Spitzer to JWST

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Introduction

The Spitzer Space Telescope has revolutionized the observational characterization of exo-planets by detecting infrared emission from hot Jovian systems. At present, measurements have been reported for five systems (Deming *et al.* 2004, 2006, 2007 Charbonneau *et al.* 2005, Harrington *et al.* 2006, 2007). The detection of infrared emission from hot Jovian exo-planets has stimulated extensive theoretical work on the atmospheric structure and emission of these planets. Constraining the model predictions for infrared emission from hot Jovian atmospheres is an important motivation for current observing programs. Though (broad-band) photometric detections of the emission of planetary atmosphere mark a huge leap in our capabilities to study exo-planets, these detections do not provide us with detailed information on the atmospheric chemistry and temperature structure. For this spectra are needed. Spectral characterization of hot Jovian exo-planets is, therefore, a high priority and is essential for understanding atmospheric composition and properties. Recently, the announcement of a Spitzer/IRS detection of a featureless emission spectrum from HD 189733b (Grillmair *et al.* 2007) and an emission spectrum containing emission features from HD 209458b (Richardson *et al.* 2007, Swain *et al.* 2007) has generated great interest. These hot Jovian systems orbit extremely near to their central star (<0.1 AU), which results in the star eclipsing the planet or vise versa. By observing spectra when these systems go trough an secondary eclipse, and taking the difference spectrum, as graphically depicted in the top left figure, the spectrum of the planet can be recovered. In the following we discuss the current Spitzer capabilities using the Swain et al. 2007 results on HD 209458b, and give an outlook into future Spitzer and JWST observations.

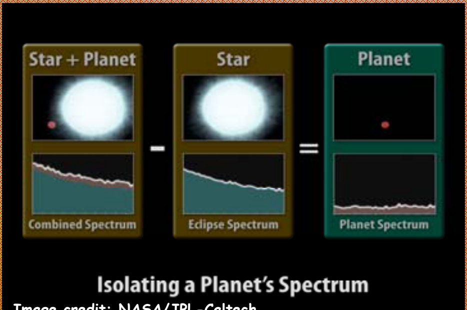
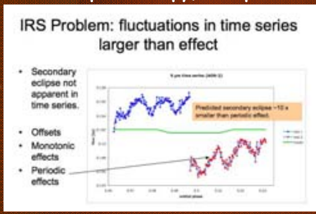


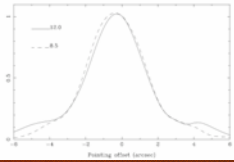
Image credit: NASA/JPL-Caltech

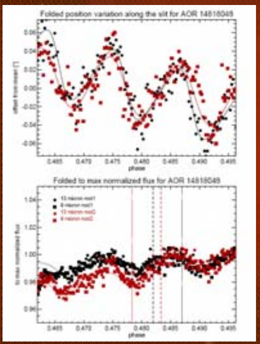
Calibration of Spitzer spectroscopy

Spectroscopic detection of exo-planet emission has proven to be challenging. Space-based infrared spectroscopy, as Spitzer is providing, is in principle ideally suited for the task, due to the absence of an atmosphere, improved signal-to-(SNR), and instrument stability. However, observations with the Spitzer IRS instrument are complicated by systematic errors that are large compared to the observable signature as can be seen in the left figure. One can observe (i) a flux offset between nods, (ii) a periodic flux modulation, (iii) initial flux stabilization, and (iv) monotonic flux drift within a nod. These temporal changes are not random; a scatter diagram shows that flux density values are highly correlated (correlation coefficients of 0.99).We find that these four major temporal flux density changes listed above are caused by (in order of importance) errors in telescope pointing, background subtraction, and latent charge accumulation.



Here we will only discuss the errors due to telescope pointing. As the spectrograph of Spitzer uses a narrow slit compared to the PSF, small pointing offsets perpendicular to the slit can lead to significant flux losses as the source is no longer properly centered within the slit. The figure to the right shows the fraction of the source flux falling into the slit as a function of pointing offset for two different wavelengths. For a know offset one can use this function to correct for any wavelength dependent flux losses.

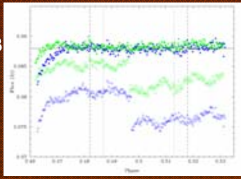




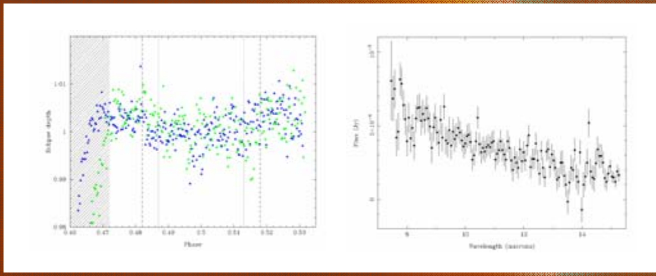
To determine the initial pointing offset, pointing drift and periodic motion we used both the spatial and spectral axis. The top panel of the figure to the left shows the source position along the slit's spatial axis. The lower panel shows the corresponding behavior of the source flux. We modeled the pointing error periodic motion in both the spatial and spectral axis. This leads to an elliptical motion that creates a symmetric profile about individual maxima and minima. The asymmetric profiles in these data require the addition of a harmonic term for angular velocity; when this is incorporated, the pointing error is given by

$$\dot{\theta} = \dot{\theta}_0 + A_\theta sin(\omega t - \phi_\theta),$$
$$x = x_o + m_x t + A_x cos[\omega\theta(t) - \phi_x],$$
$$y = y_o + m_y t + A_y cos[\omega\theta(t) - \phi_y],$$

where t is time, x is the position parallel to the slit axis (the spatial dimension on the array), y is the position perpendicular to the slit axis (the spectral dimension of the array), x_0 and y_0 are initial offsets, m_x and m_y are the linear drift terms, θ is the angular coordinate, A_x, A_y and A_θ are the amplitudes, ω is the frequency, and ϕ_x, ϕ_y and ϕ_θ the phases. The resulting fits are also plotted in the left figure. We applied a similar scheme as described above also for a series of measurements of the calibrator star eta1 Dor, providing us with an absolute flux calibration for the observations of HD209458. The absolute flux calibrated photometric time series including pointing corrections can be Seen to the right. Note that the first 15 min of observations are being influenced by a latent charge accumulation, not corrected here. These calibrated and corrected data allowed us to determine the eclipse depth and to extract the planetary spectra shown in the right column on this poster. The SNR of the final calibrated data is about ~100. Though this would be enough to also observe the nightside of the planet, our current calibration has not reached the dynamic range limit of the instrument, which is a factor of 2 higher, and we believe further improvements in the calibration method, together with changes in the observing strategy, could considerably improve the measurement SNR.



Current Results and Outlook: From Spitzer to JWST



The above figures show the secondary eclipse (left) and resulting spectrum (right) of HD 209458b. Using the IRS data, we have determined the broad-band eclipse depth to be 0.00315 ±0.000315, which is consistent with reported IRAC and MIPS photometry. The eclipse depth implies significant redistribution of heat from the dayside to the nightside. Over much of this spectral range, the planet spectrum is consistent with featureless thermal emission, consistent with a T~1100 K black body. We do not find evidence of a strong "peek" at 10 micron predicted by some models due to dust. Between 7.5 and 8.5 μm, we find evidence for an unidentified spectral feature. This spectral modulation implies that the dayside vertical temperature profile of the planetary atmosphere is not entirely isothermal.

The thermal emission spectra of HD 209548b and HD 189733b mark an exciting new step in panetary science. Upcoming Spitzer observations will further enhance our knowledge of the atmospheres of these hot Jupiters by observing additional systems and expanding the wavelength coverage of the current observations to 5 μm. Excess to these shorter wavelengths will allow for a clear detection of $H2O$, CO and $CH4$. Having the possibility of enhancing the SNR of the Spitzer observations still with a factor of 2 by improving the current calibration, detection of even relatively weak features should impose no problem. A further step will be observing the planet not only during secondary eclipse but during different orbital phases. Similar as with the IRAC observations by Knutsen *et al.* 2007, one can than derive the planets temperature as a function of longitude constraining heat redistribution models. In addition to this changes in the chemistry of the planetary atmospheres from day- to nightside will be revealed.

Building on the Spitzer results, JWST can be expected to greatly enhance our knowledge of planetary atmospheres. With an diameter 8 times larger than Spitzer, an increase of the SNR in the shot-noise limit of 8 (assuming an identical spectral resolution) can be achieved. This will make it possible to observe a far larger sample and truly provide comparative planetology. Another big step forward will be the superior spectral resolution of ~3000 of the MIRI and NearSpec instruments, which will provide us with the exciting possibility to detect pre-biotic molecules in exo-planetary atmospheres. We expect that current and future surveys of M stars will find transiting exo-planets in the habitable zone. These are ideal targets for a JWST search for organic molecules. In addition, JWST will be able to study changes in the atmosphere caused by global-scale weather which is expected on the slowly rotating, tidally locked exo-planets. Detailed JWST spectra of the exo-planet atmosphere in both emission and absorption will allow a detailed understanding of the relative importance of thermo- and photochemistry in these objects.