Status Report on SOFIA Exoplanet Transit Capability

Ted Dunham
Georgi Mandushev
Daniel Angerhausen
Introduction

• Update on HD189733b transit observation on 10/1/2013 (UT) with FLIPO
  – Originally Avi Mandell’s FLITECAM-only proposal
  – Search for water in HD189733b using Pa alpha filter
  – Morphed into a FLIPO demonstration transit

• Talk Outline
  – Introduction and practical matters (Ted)
  – Data analysis, systematics, and results (Georgi)
  – User’s perspective and independent data analysis (Daniel)
  – Wrap-up (Ted)
Scientific Value of Transits

- Atmospheric structure and chemistry
  - Rayleigh scattering, scale height
  - NIR spectrophotometry
    - Search for presence of interesting compounds (e.g. water, methane)
    - Appear as apparent radius differences with wavelength
- Heat exchange -- exoplanet weather
  - Phase functions, secondary eclipse
- Starspot and plage size and color temperature
- Primary interest is in 1-5 micron range
- More later from Daniel
Observational Issues

• The prize is not easily grasped.
• Need to measure small features in shallow transits
  – Overall fractional error \(~\text{few} \times 10^{-4}\)
• Not easy for anybody – systematics dominate at this level
  – Kepler, HST, Spitzer, ground-based systems all have problems. We do too.
    • Bill Rose: “Why don't you pick something hard to do??? Geeeesh.”
  – Known problem areas for SOFIA:
    • Water vapor, ozone, and Rayleigh extinction; static air density, Mach number (?), pointing, jitter, and focus.
  – Reliable housekeeping data essential for correcting these
  – Some instrument-specific details can be important
• Differential photometry (field standard) is NOT a cure-all
  – Usually doesn’t happen anyway
  – When it does it works best if the differential correction is small
Systematics, I

- **Extinction**
  - Rayleigh scattering (optical; proportional to static pressure and airmass)
  - Ozone (optical)
  - Water (IR)
  - Volcanic aerosols
    - Can vary by 0.1-1%
    - Episodic problem
    - IR impact uncertain

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Nabro eruption, 13 June 2011 (Bourassa, et al. (2012))
Systematics, II

• Aero-optical PSF effects
  – Optical PSF dominated by shear layer scattering
    • Refractivity ($\nu = n-1$) is proportional to density
    • $\delta \rho / \rho_{\text{static}}$ is roughly constant
    • Image FWHM expected to scale with static density
    • Very broad PSF wings interact with aperture
      – Perceptible additional enclosed flux across entire HIPO field!
    • Rose expects FWHM dependence on Mach number
      – We don’t see this, at least so far
  • So far no obvious “dome seeing” contribution
Systematics, III

• Other PSF-related effects
  – Defocus, especially early in the flight
    • Really should have automatic SMA_T1 focus update
  – Jitter (causes erratic enlarged time-averaged PSF)

• Pointing noise
  – To first order, fixed by (proper) flat fielding, right?
    • Never really works right. Stable pointing is best, decorrelated pointing errors are second best.
  – Jitter increases noise, but uncompensated drift is fatal
    • Exoplanet science occurs at low frequency
Systematics, IV

• Instrument-related effects
  – Carried out lab tests for HIPO (with small PSFs)
    • Millimag photometric changes occur with large CCD temperature changes
    • Perceptible CCD controller temperature sensitivity
      – Important to operate controller uniformly. *Kepler* lesson.
    • *Kepler*-like image position effects noticed but overwhelmed by the airborne environment
    • Overscan may be a useful decorrelating variable
  – No similar information available for FLITECAM
Differential Photometry

- SCAI-9 Test
  - HD 85216 (V=8.4, A3) and BD+19 2271 (V=8.8, F5)
  - 19” aperture (red) 26” (blue), open filters
  - Raw photometry (left), differential (right)
  - Systematics still there in differential light curves at a few millimags
Transit Observation Circumstances

• Several problem areas known before takeoff
  – Very little baseline before the event, none after
  – Short FLITECAM LHe hold time
    • Short flight; must observe transit first thing. Focus unstable.
  – WVM not installed
• In-flight problems
  – FPI failed at start of leg (blown circuit breaker); fell back to FFI
    • HIPO guiding not properly tested, so didn’t attempt that
    • Lost the little pre-transit baseline we had
  – Pointing was very poor. FFI in poor focus for a while.
• Post-flight problems
  – During data analysis found electronics-related problems in FLITECAM affecting global reset and co-adding.
  – No useful FLITECAM data obtained.
HIPO Observational Details

• Observed in Basic Occultation mode
  – Full frames to maximize field standard possibilities
    • Field standards all very much fainter than target.
  – 3 second integrations on red side, Sloan z’ filter
    • \( \sim 2700 \) measurements
  – 7 second integrations on blue side, Johnson B filter
    • \( \sim 1000 \) measurements
  – Broken into chunks to keep file sizes manageable

• Filters selected to avoid ozone problems
- Image Processing
  - CCD Reductions
    - Raw frames are overscan & bias-subtracted
    - Trim off prescan, overscan, and dark pixels
  - Flat-fielding
    - High S/N twilight sky flats taken during line ops
    - B flats show laser annealing pattern, 1-2% p-p
    - Sloan z' flats show only overall curvature

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Trouble in Flat-Land

Photometry shows strong position dependence – Incorrect flat – Most likely due to sky seen around secondary

Solution (for now) – Skip flat-fielding on red side – Fit and subtract overall curvature on blue flat but retain annealing pattern. Flatten with that.

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Photometry

- Aperture photometry – Large aperture (60") to reduce effects of focus, jitter, centroiding
  - Bright target; sky & read noise contribute each ~10% of shot noise on target even in huge aperture

- Why not PSF fitting?
  - PSF fitting best in very crowded fields
  - Shear layer PSF is not well represented analytically
  - PSF shape is variable anyway
  - Bad experience with PSF fitting in PSST context
  - But … did use PSF fit to estimate z' brightness ratio of target & companion and for FWHM/ellipticity
Corrections:

- ExHnHon: – 6%/airmass in B, 0.5%/airmass in z’ at 40000 s.
- Rayleigh scattering and ozone (mostly avoided)
- CorrexHon based on measurement of Landolt standards on 2013-10-01 UT flight

StaHc density:
- Measured during shear layer test on 2013-01-24 flight
- 0.01 kg/m^3 density change => -6.8 x 10^-4 photometric change
- Significant correxHon, ~ few millimags

Mach number:
- No noHceable dependence seen so far

PosiHon dependence:
- Can be a few percent, depending on flaXening details
- Typical: ~ few x 10^-5 per pixel of moHon

SCTF 1/29/2014
Corrections, II

- Setup leg, 2013-09-27 UT
  - Short leg, little change in density or Mach number
  - Strong positional effects
    - Star moved across field
      - Setting up position on FLITECAM array
  - Position correction
    - Fit and subtract polynomial of position jointly in X&Y
    - Use this approach for correcting transit data
Corrections, III

- Re-measure density/Mach/focus dependence
  - Intended to do this with FLITECAM -- didn’t work
  - Beautifully executed test on 2013-10-01 flight
    - Density section ruined by clouds at 40000 feet!
      - Will try again next month with FLITECAM

- Why the bump in the Mach number test?
  - Centroid offset
Light curves
(bias subtracted, Blue side flattened)
Transit Fit, I

• To fit or not to fit:
  – Ideally fit for astrophysical parameters only
  – Important corrections need fitting too
  – Try to fix the parameters you can

• Fix variables we think we understand
  – System parameters from HST data; limb darkening
    • Epoch, period, impact parameter, radius, inclination
  – Fix density.
    • When fit the coefficient becomes too large to believe
    • Possibly real structure is obliterated
    • Weak point – we still need a better handle on this
Transit Fit, II

• Fitted parameters include:
  – Flux zero point in B and z’
  – Differential atmospheric extinction in B & z’
    • After removing measured extinction from Landolt stars
  – Centroid corrections
    • Differential X and Y offsets in B and z’
    • Radial offset in B and z’

• Fit is done simultaneously to both datasets
Transit Fit, III

• What can we say about this?
  – How much is real?
    • 189733 is active
  – How much is not?
    • Without baseline, can’t tell
  – Density glitch is close to “star spot”.
    • Cause & effect or coincidence?
    • Klaus Huber’s model - hmmmmm
Switch to Daniel’s File Here
Improvements for next time

- Get good FLITECAM data!
  - Need WVM operating; calibration not required
- Repeat shear layer test with FLITECAM (no clouds)
- Observe bright stable star pair for a LONG leg
  - Search for other possible systematic effects
- Keep pointing and focus under tight control
  - HIPO guiding, possibly automatic focus update
- Get plenty of pre- and post-transit baseline!
Longer Term Issues

• Deployments will be involved
  – Short SOFIA leg lengths are a serious impediment

• Sunrise constraint needs to be eliminated

• Install Nasmyth blower
  – Cool FLIPO periscope & FLITECAM window
  – Biggest background contributors for FLITECAM

• Install the fully reflective tertiary
  – Systematics dominate only when shot noise is low enough.
  – We’re stuck with an observing efficiency hit of 20% to 60%
    • Using the FPI only wins back part of that
  – But it’s worse – with time-limited events you can’t even make it up with more observing time.