Surveying the Brightest Stars for Exoplanets with a Small Telescope in Space

Conference in Honor of Bob Fosbury
Villa Aureli, Perugia, 23-25 May 2011

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Planet Hunting

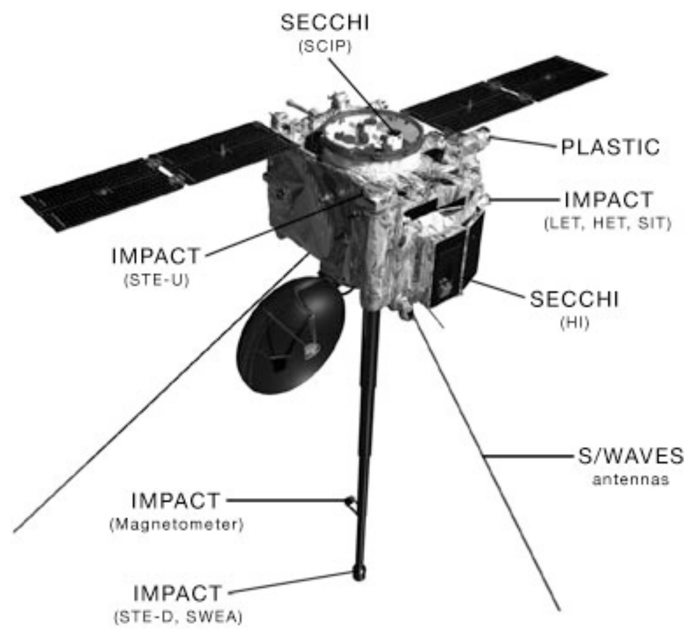
- Methods of finding extra-solar planets
  - Indirect – gravitational or photometric influence on host star
    - grav. tug on host star: RV (0.1-10 m/s), ASTR (3-300 μas)
    - special geometry: TRAN (0.01-1%, hours), ML
  - Direct – (spatially) separate planet light from host star
    - reflected light (Opt) – coronagraphic imaging
    - thermal radiation (MIR) – interferometric imaging
- Current status – >550 planets and counting (quickly)
  - RV – most productive (~80%), limited utility (M_p•*sin(i)*,*P*,*e*)
  - TRAN – second most productive (~15%), best characterization (M_p,R_p,*P*,*e*,*T*,*atmosphere*), limited for outer planets (rare events)
  - ML – ~10 known, good for statistics, best sensitivity for small & outer planets, limited utility (can not repeat!)
  - DI – few known, sensitive to outer planets (currently), high potential for characterization (colors, spectra)

Brighter is Better!

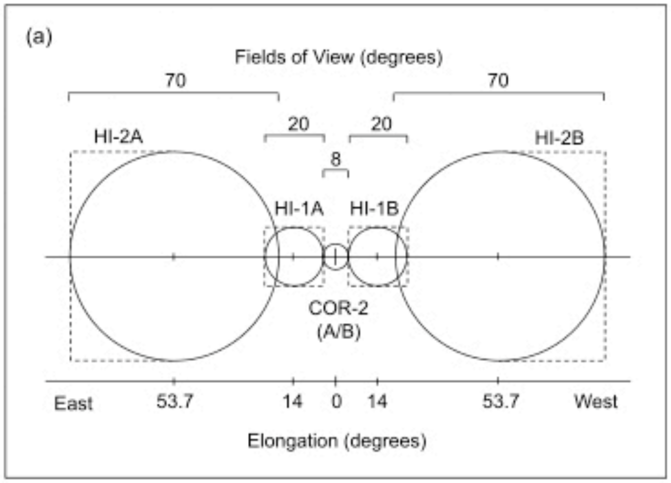
- Transits – the best buy for the money!
  - TRAN+RV => key planet parameters: M_p, R_p, P, e, => mean density (planet composition)
  - "in-out" transit: photometry => temperature (T), temperature map; spectroscopy => atmospheric composition (H_2O, CH_4, CO_2, etc.)
- Biggest limitation problem: number of photons!
  - Effects are small: need very high S/N to measure transits, RV, TTV, astroseismology, etc.
  - Differential techniques require very high S/N, e.g., atmospheric effect is proportional to $2(hR_p/R_s^2) \leq 10^{-5}$
- Exoplanets transiting bright stars are "crown jewels"
  - Allow high precision follow-up research with existing facilities, both ground- and space-based
  - Next suggested space project - all sky survey for bright stars ($<10^m$)

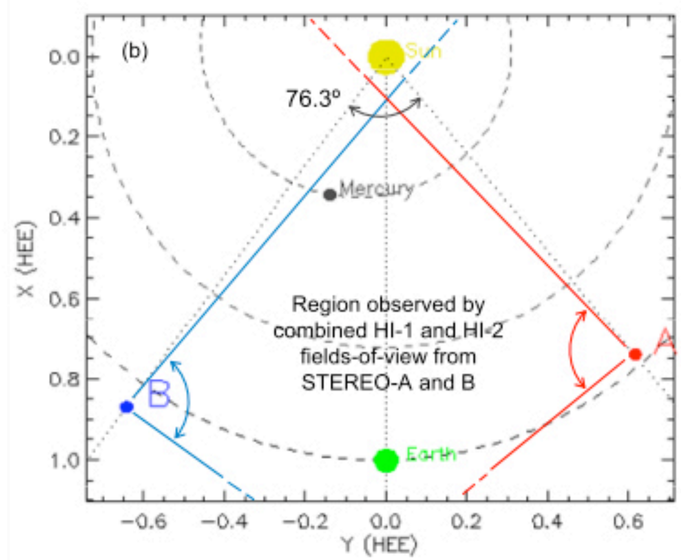
STEREO Mission

- STEREO = Solar-TErrestrial Relations Observatory – third mission of NASA's Solar Terrestrial Probes probes
- Prime objective: provide stereoscopic view of the Sun and of the CME as they propagate toward Earth
- Two identical spacecrafts on heliocentric orbit – ahead and behind Earth
- SECCHI – 5 instruments
  - Lyot coronagraphs: COR1, COR2
  - Heliospheric Imagers: HI-1, HI-2
  - Extreme UV imager: EUVI



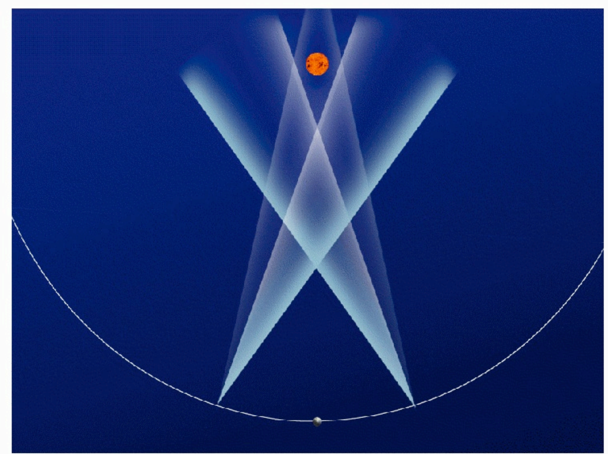
STEREO Heliospheric Imagers



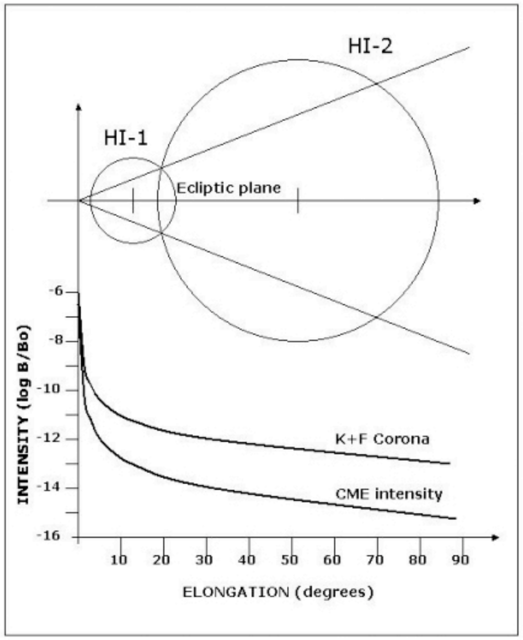


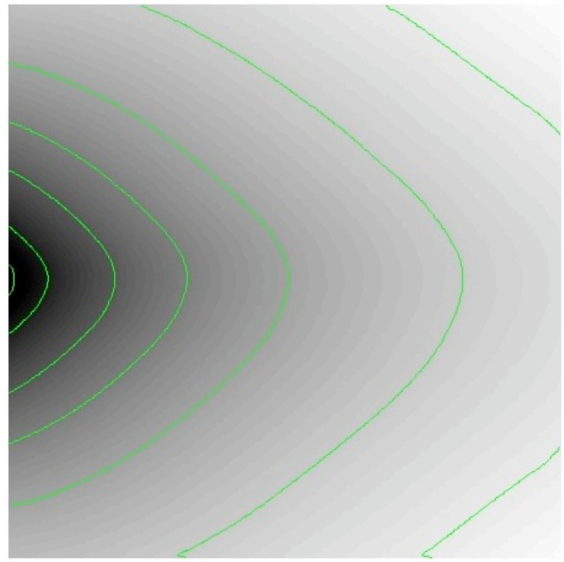
- HI – externally occulted coronagraphs
- HI-1: 20° FOV, pointing ~14° from Sun-centre, ecliptic
- HI-2: 70° FOV, pointing ~54° from Sun-centre, ecliptic

Overlap from HI-1 and CORs



HI-1 Images





Right: Major contributions to background

Left: typical HI-1 background. Contours are 90, 50, 20, 10, 5, 2, 1% of peak

- HI images: background, stars, CME, planets, etc.
- Background: F+K corona, scattered light rejection level 1/10 below the zodiacal light ($\sim 10^{-13} B_{\odot}$)
- Stars: visible down to 12-13^m, for this project <10^m

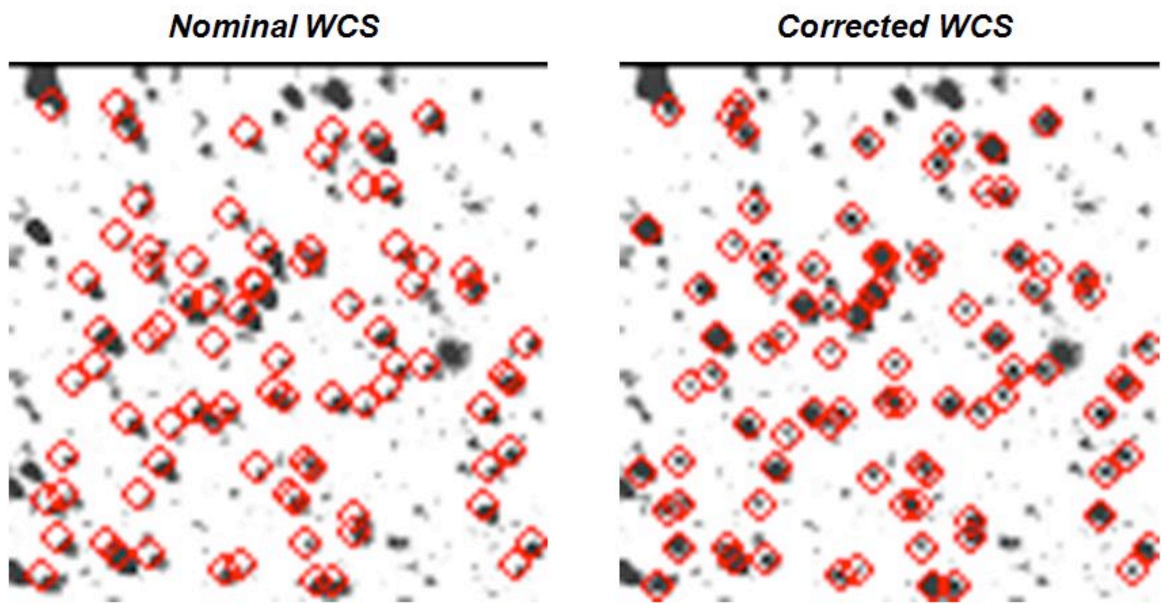
HI mode of operation

- Mode of operation:
  - series of short exposures
- On-board image processing:
  - CR removal: pixels>5σ replaced with same from previous image;
  - Bias & trim;
  - Number of images added;
  - Binning 2x2
- Download:
  - 36 HI-1 images and 12 HI-2 transferred to Earth per day

	HI-1	HI-2
Individual exposure times	30 s	50 s
Exposure cadence	60 s	60 s
Number of images summed	40	99
Total exposure time	1200 s	4950 s
Exposure cadence	30 min	99 min
Summed image cadence	40 min	2 hours

- The choice of parameters listed in Table above leads to:
  - The brightest of the F-corona is ~60% of CCD dynamic range
  - Only stars <2.5^{m} are saturated
  - Drift of star field does not lead to a significant smearing

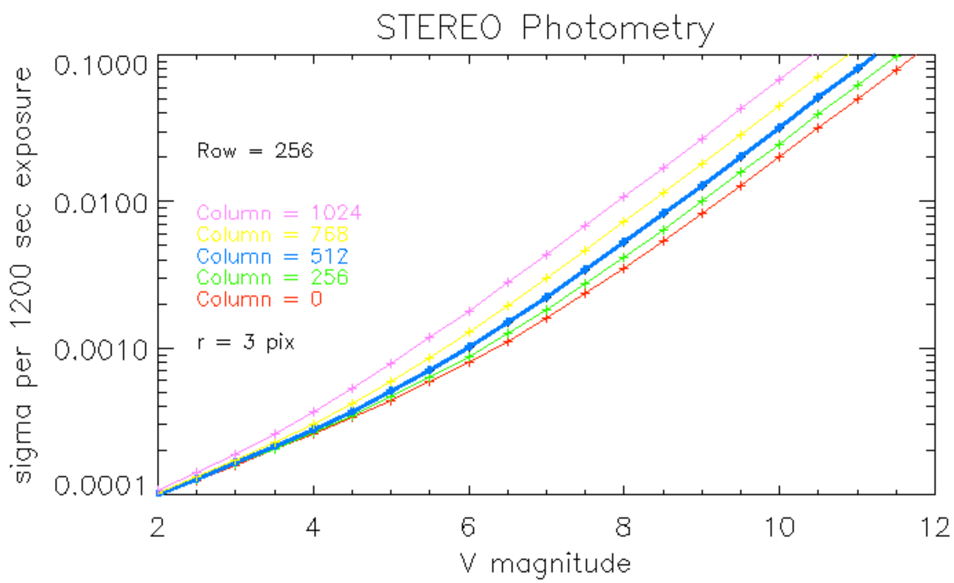
Star Input Catalog and Astrometry

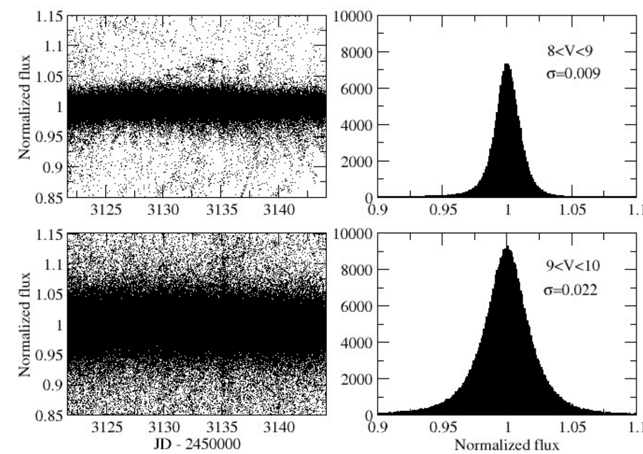


Tycho 2, V < 9

- Use Tycho-2 catalog (99% complete to 11.5^{m})
- This project input catalog: ~75,000 stars $<10^{m}$
- Improved astrometric solution: based on all Tycho-2 stars. Original solution good to 7° of center, but FOV=20°. New solution can locate stars to <0.1 pix across entire FOV.

Photometric Accuracy





Left: calculation for aperture photometry with r_{ap}= 3 px

- Included terms: total count rate from star (C_s, e-), background count rate (C_b, e-), detector read noise (*RN=15* e-), number of pixels in aperture (N_p=28), number of detector reads (N_r=40), total exposure time (T_{exp}=1200 s)

Right: actual data – aperture photometry of ~3000 stars extracted from 30 days of HI-1A data. Low-frequency trends are removed by fitting low-order polynomials.

Transit Detection Sensitivity

For photometric series:

$$SNR_t = (d_t/\sigma)n_t^{1/2}$$

d_t – transit depth
σ – photometric error per data point
n_t – total number of data points during transit

SNR for transit detection		
mag	Jupiter	Neptune
3	600	90
4	377	57
5	155	23
6	68	10
7	28	4.2
8	11	1.7
9	4.5	<1
10	1.8	<1

Data in Table are estimates for two cases:

1. Typical hot-Jupiter – Jupiter size planet transiting G-type star, P_t=3 d, d_t=0.01, τ_t=3 h
2. Typical hot-Neptune – depth of transit 1/8 of Jupiter, other assumptions same as for hot-Jupiter

The SNR_t is calculated for photometric data series produced from one pass through the HI-1 imagers only, i.e., over 40 days during one year (~1400 points). By now there are at least 4x as much data.

Expected Yield

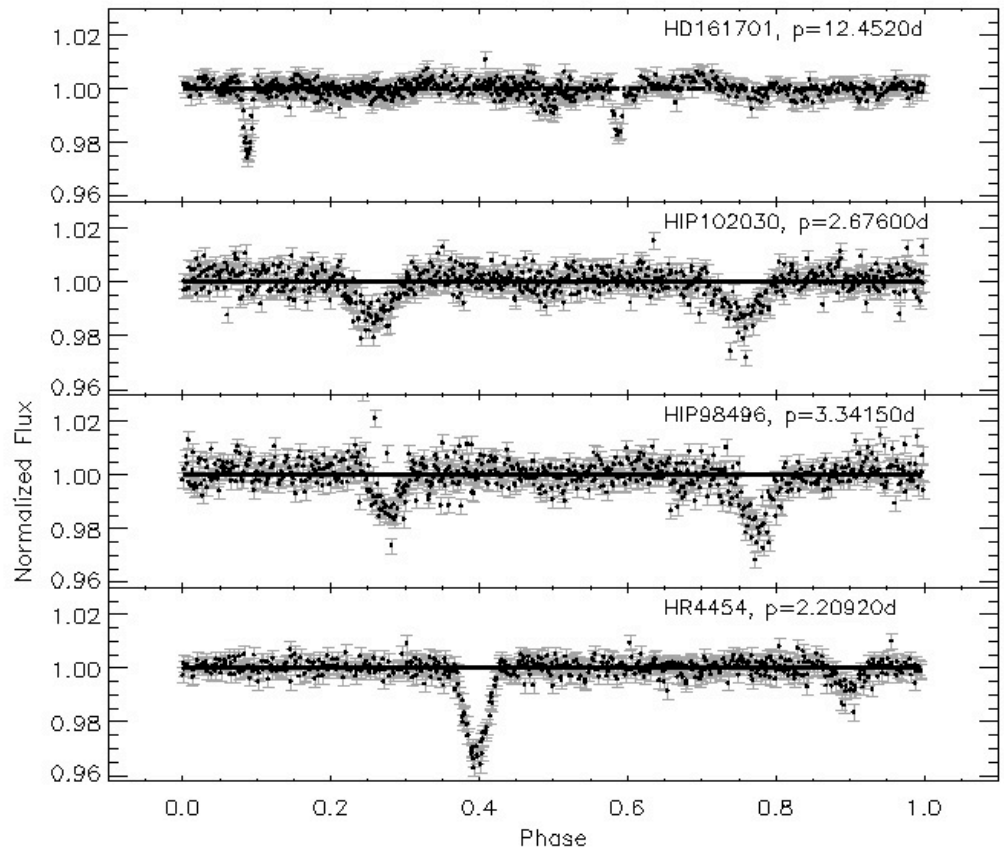
	TESS	STEREO HI-1
Sky area covered	All sky (40,000 deg^2)	18% sky (7200 deg^2)
Number of stars	$\sim 2.5\times10^6$	~75,000
Magnitude range	4.5-13.5 (SDSS r)	2.5-10 (~600-720nm)
Transit periods, P_t	1-30 days	1-20 days
Transit depth, d_t	0.0001-0.04	0.001-0.04
Transit duration, τ_t	0.02-0.5 days (0.5-12 h)	0.02-0.5 days (0.5-12 h)
Number of transits, n_t	≥ 3	≥ 3
Expected yields: planets FP	~1500 (J+N only) ~13000	~10-15 (J+N) ~400+

- Expected yield estimated based on Brown & Latham (2008) as applied to TESS, a proposed all-sky transit survey
  - Integrating probability density of all classes of objects (real planet transits and false positives) in the range of interest for planetary transits (basically transit period P_t, transit duration τ_t, and transit depth d_t), scaled to the number of target stars.
  - Expected yield: planets=1/2300 stars, FP/planets=~10:1
- These estimates confirmed by:
  - CoRoT: (Almenara et al. 2009): yield 1/2100, real planets 12% (8:1 FP)
  - Kepler: better, but there is serious pre-selection

Transit-like events in real data

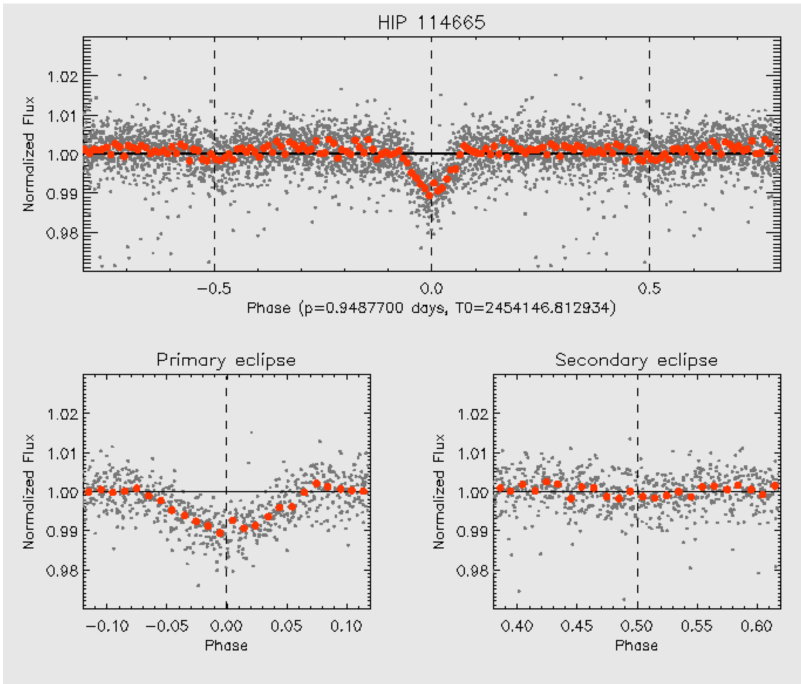
Can we see planet-like transits?

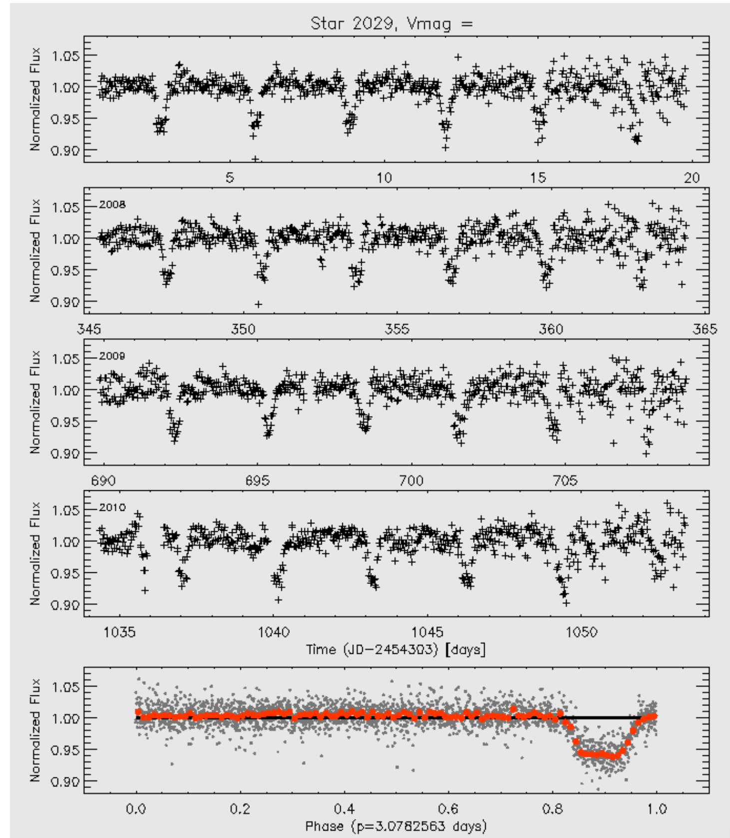
Yes, we can!



Over 100 new EB found. Data shown are from 20 day sequence of HI-1A images obtained in 2009. Not optimal flat-field correction is applied, de-trending is very basic. LC are folded by orbital period, phases are arbitrary. Eclipses range from ~3.5% to <1%. Available data points are up to 7x more.

Many false-positives …

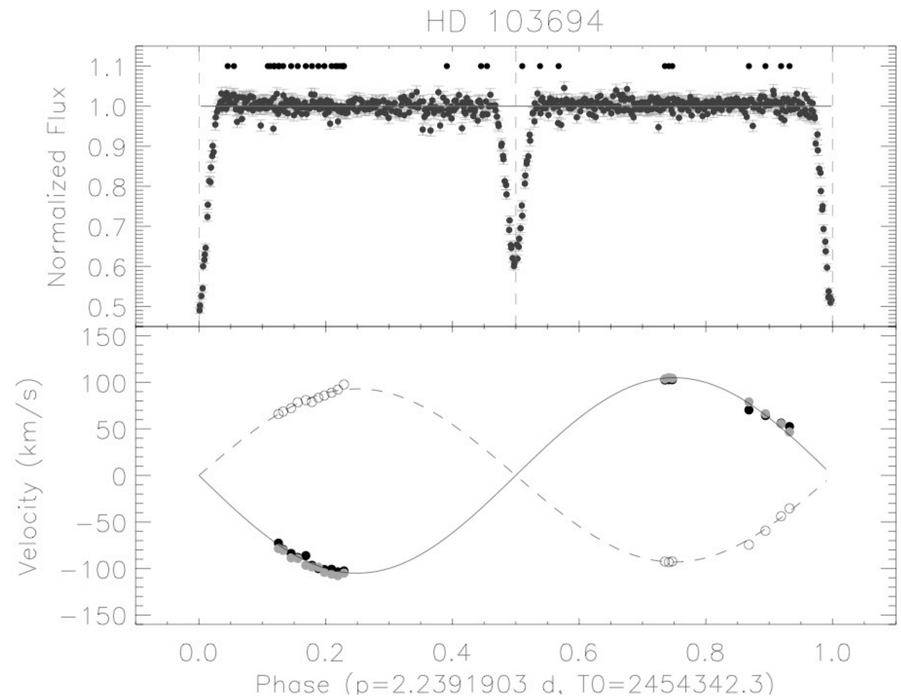




- ✧ A typical chance projection of EB – there is a known 3 mag fainter X-ray EB right at the edge of photometric aperture …
- ✧ Another EB – likely a small star transiting a giant one, so many of the characteristics are similar to a planet transit …

Follow-up Program

- ✧ Primary goal – rejection of false positive (FP) events and characterization of exoplanets
- ✧ Access to telescope time at several observatories with relevant instrumentation – APO (3.5m, R=30,000 Echelle, NIR & Opt. imagers), Lowell Observatory (31", 42", 72", imaging cameras), NAO Rozhen (2m, Coude, R=30,000, 60cm photometry)
- ✧ Secondary goal – follow-up study of EB
  - – Large number new EB (>100), eclipse depth from ~50% to <1%, many spectral types, several very interesting cases



Data for HD 103694 (V=9.5), a newly discovered EB of late K dwarfs. LC is form data sequence of HI-1A images. RV curve is from spectra obtained at APO (US) and NAO Rozhen (Bulgaria).

RV Selected Exoplanets

- There are over 50 stars with RV discovered planets in the STEREO area of the sky and with $V<10^m$
- Planets periods vary from a few days to hundreds days
- Data from one detector (HI-1A) and are extracted
- Initial inspection shows no obvious transits at the RV periods
- Up to 5x more data exists and more corrections need to be applied
- Also – better extraction, better period searching, etc…