Exoplanet Observations from a Balloon Platform

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Funding climate favors balloons

- Balloon platforms provide a well-known path to NASA astrophysics space missions
- Today's budget for astrophysics missions is being hit by large costs for missions recommended by the 2000 Decadal Survey
- The 2010 Decadal Survey may well emphasize cost on an equal footing with science
- Balloon experiments today can play two important roles:

  - Precursor instrument concept testing to increase TRL values, which reduces risk, and therefore cost

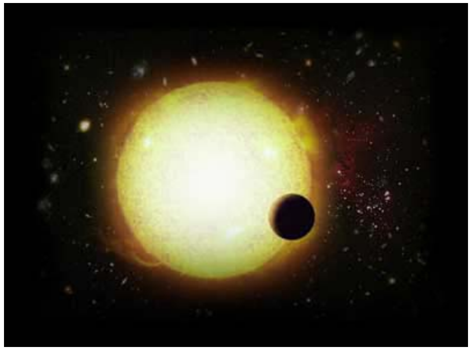
  - Scientific advancement at low cost and in the near term, compared to a space mission

Science climate favors exoplanets

- 248 exoplanets discovered in 212 planetary systems
- At the AAS meeting in Honolulu, exoplanets were the topic of 13 of the 215 oral and poster sessions.
- There are many meetings on exoplanets: i.e., NP Forum 2007 at Ames (May) , Lyot conference at Berkeley (June), Vatican summer school (June), extreme solar systems at Santotini (June), two IAU symposia in China this fall, and many others.
- Exoplanet science is the topic of choice for many young scientists.
- The American public is very interested in exoplanets, witness the story on NBC Nightly News when Gliese 581c was announced.
- Media coverage is excellent, and always positive.

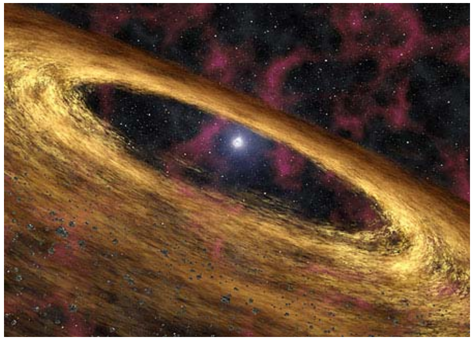
Characterization is the new science focus

- To understand planet formation, we need both characterization and detection.
- Transit observations (e.g., Na & H_2O) only probe the upper atmospheres of exoplanets, not the troposphere, clouds, & surface.
- Direct observations are needed to observe the main atmosphere, clouds, & surface.
- Coronagraphs are designed to make direct observations.

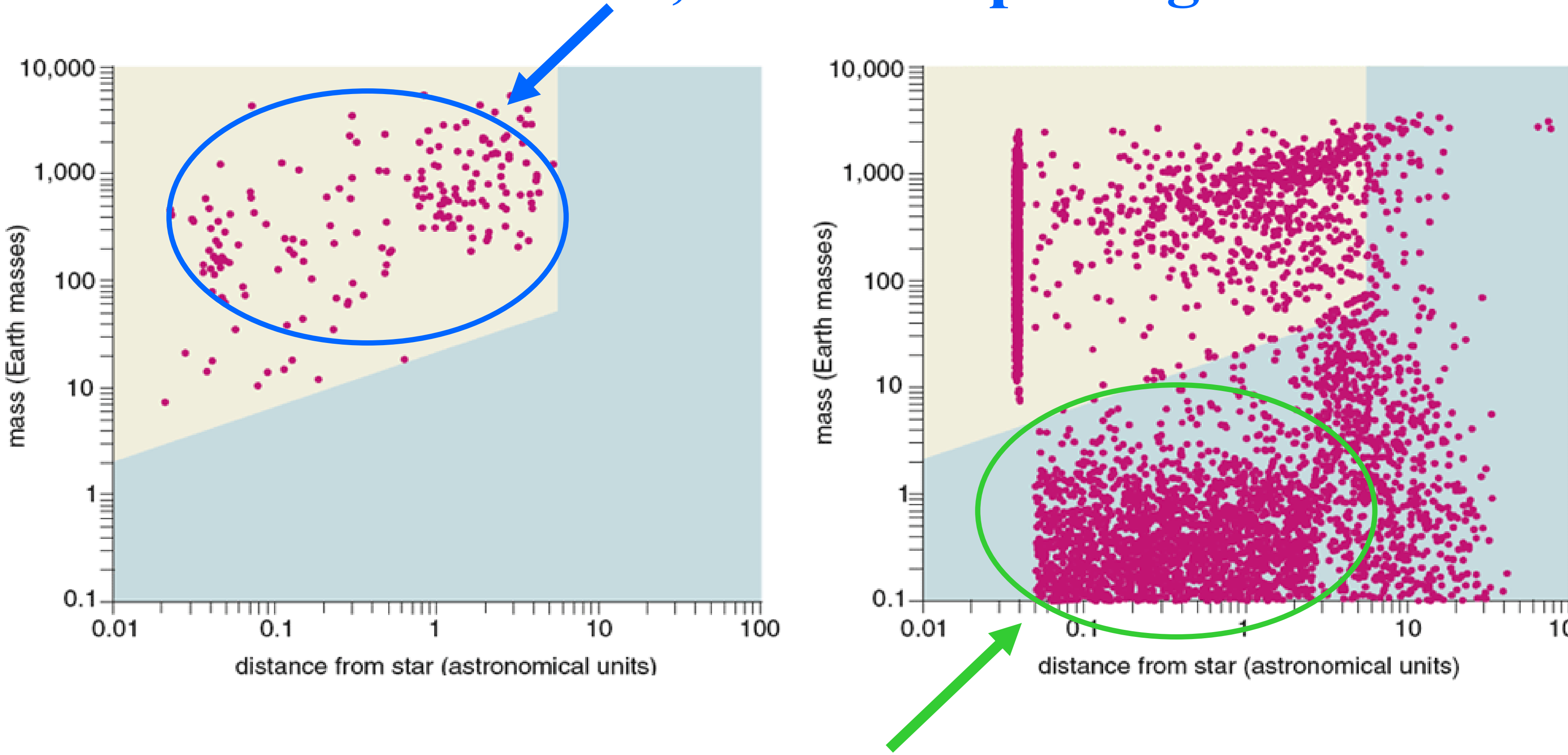


Balloon-coronagraph capability

- Directly characterize brightness and color of known exoplanets in the visible and near-infrared.
- Constrain albedo, diameter, effective temperature, cloud type, atmospheric pressure, atmospheric composition
- Search for new exoplanets
- Image debris disks

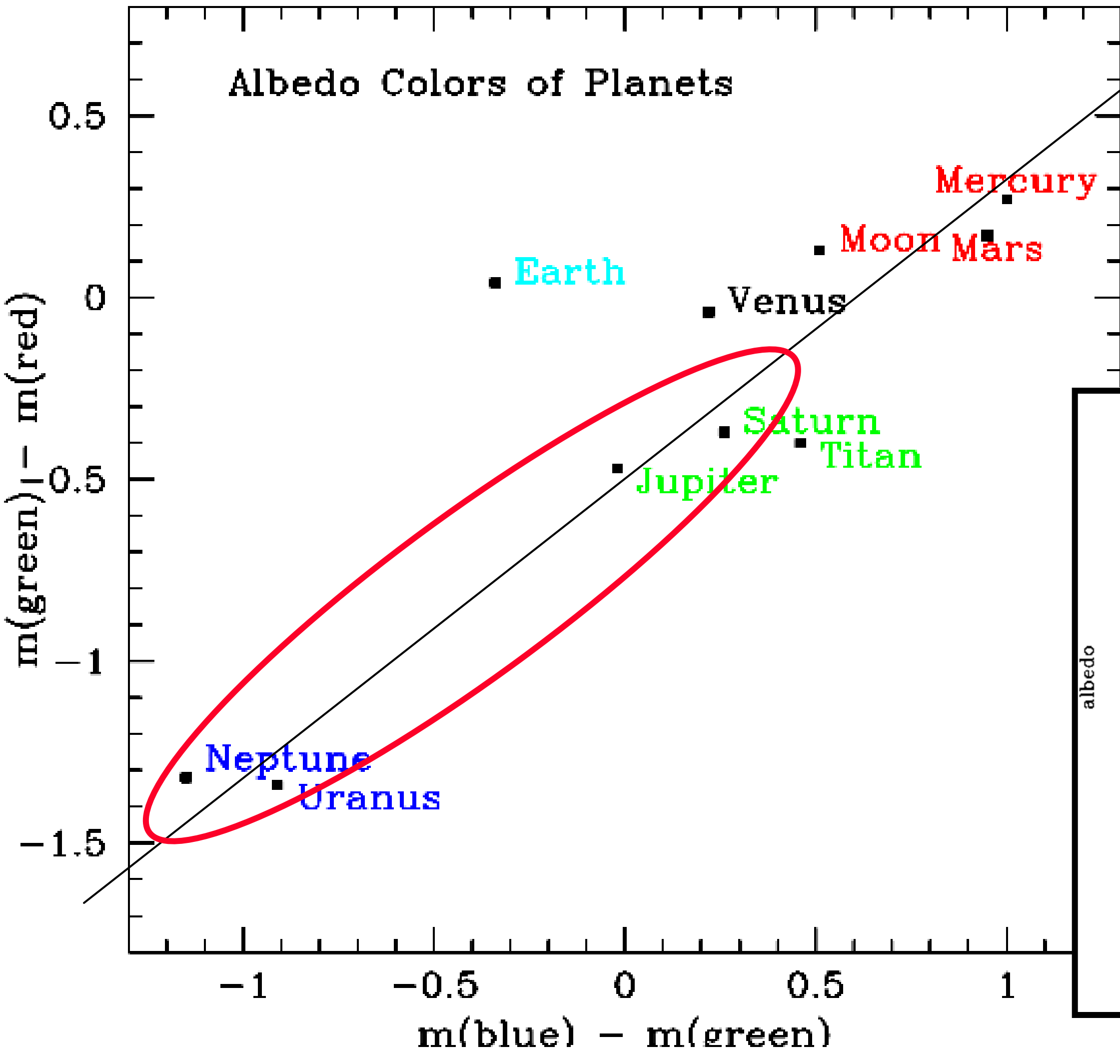


Planets found so far, Planetscope targets

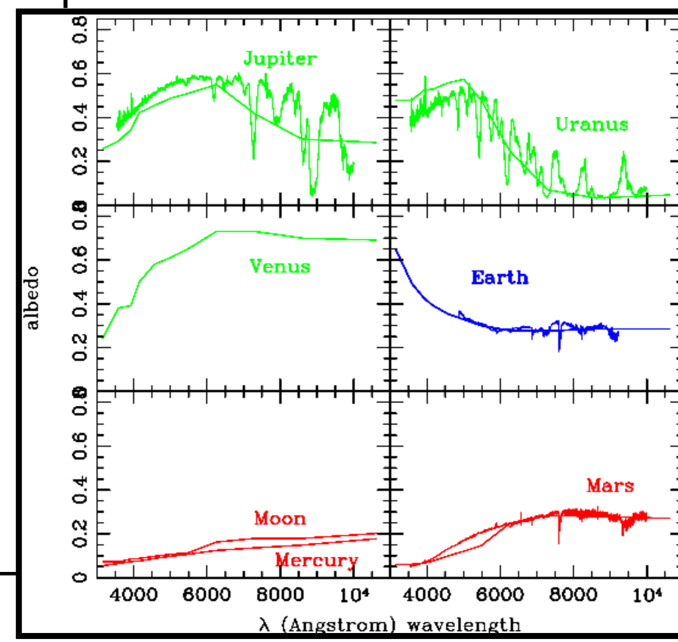


Planets we hope to find,
In a future space mission

Planetscope will measure colors of gas giants



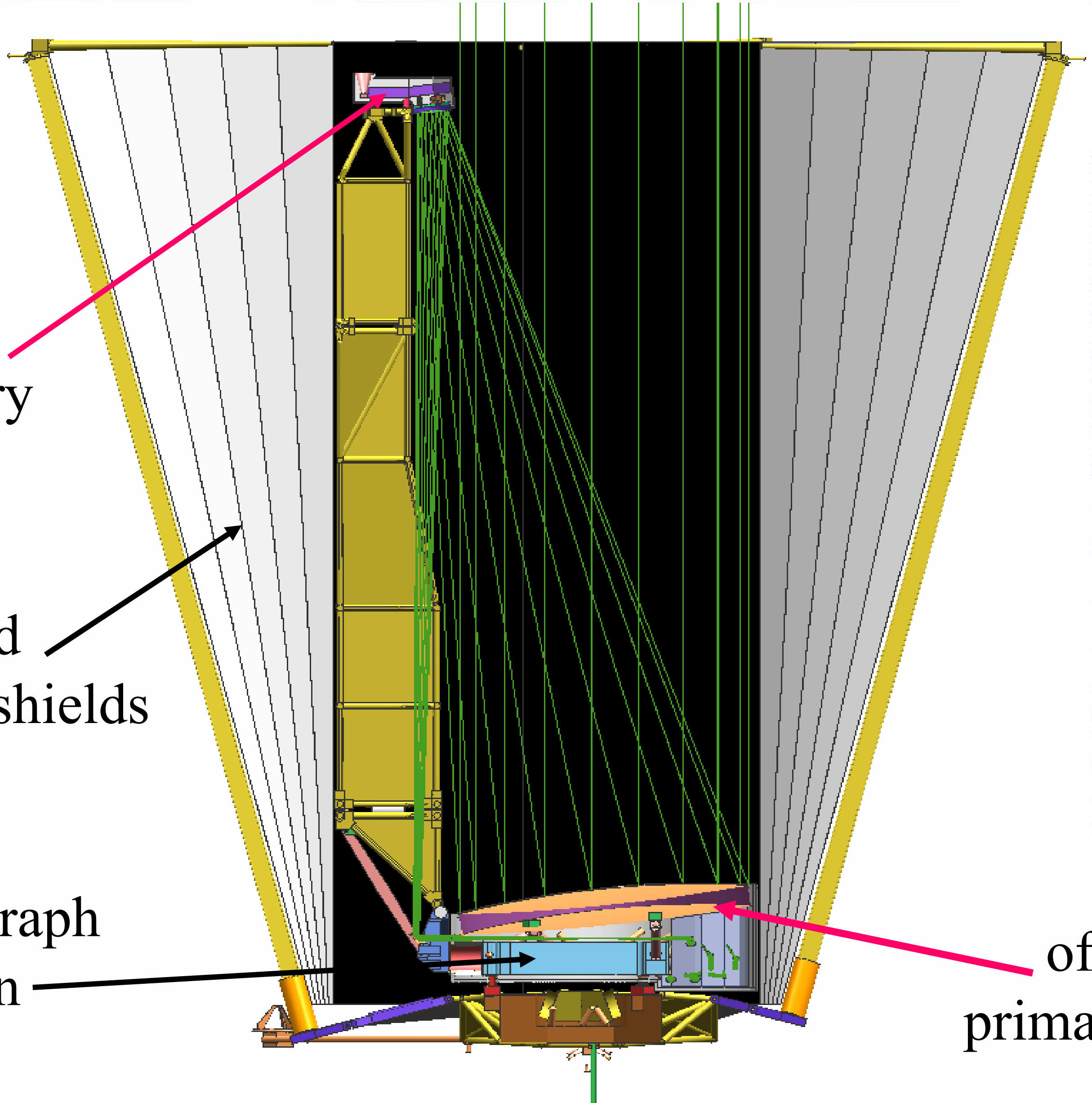
Solar system planets have colors that label them by type.



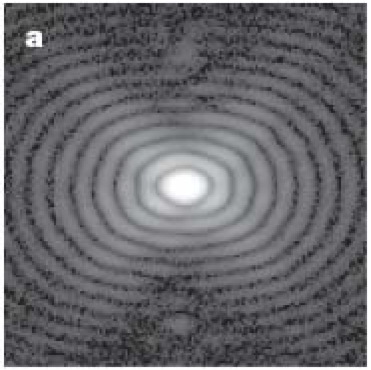
Planet spectra

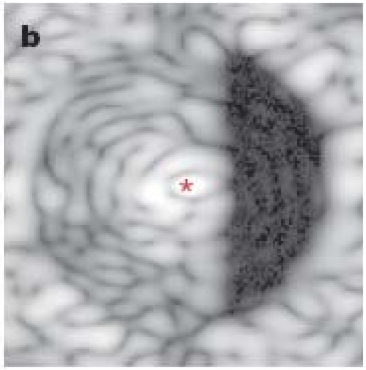
Blue (0.4-0.6 μm), Green (0.6-0.8 μm), Red (0.8-1.0 μm)

TPF-Coronagraph: Planetscope is similar but smaller



before





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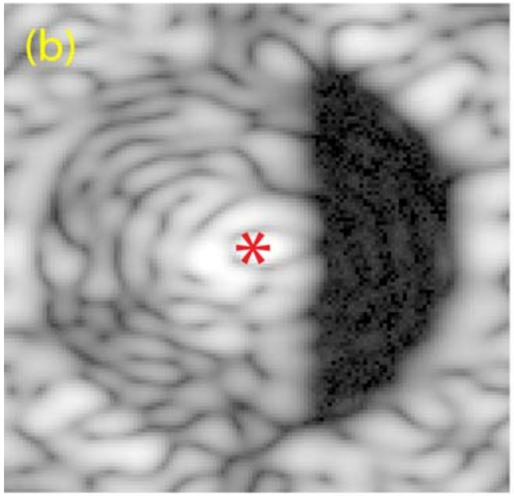
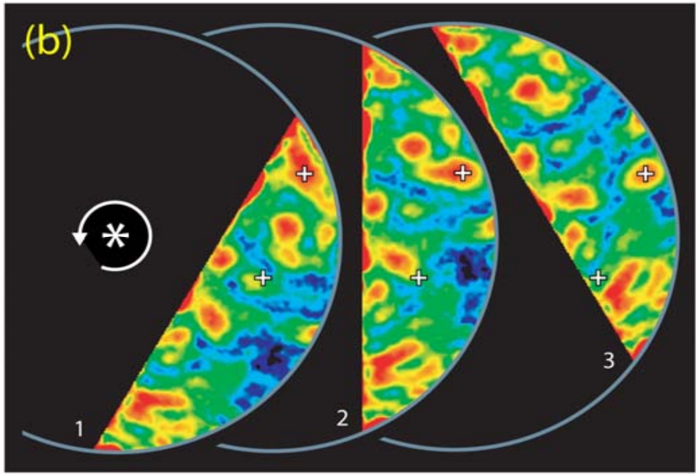
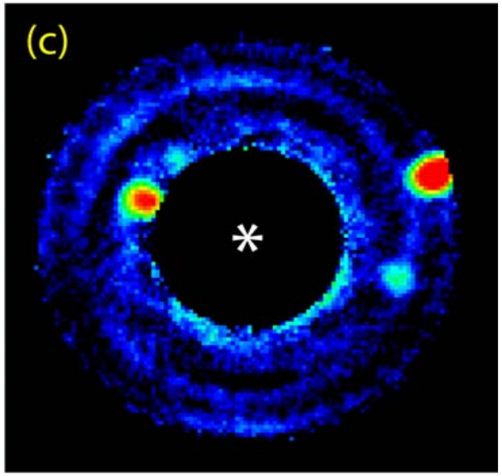
Coronagraph testbed at JPL: Planetscope will benefit







Reduce scattered light in D-shaped region

Pretend lab is in space, rotating slowly

Add up snapshots; Jupiter & Earth emerg from the clutter

Proves principle of coronagraph for detecting Earth-like planets

Trauger & Traub, Nature, April 2007

Planetscope & its Precursor

- ***Planetscope*** is a balloon-borne coronagraph concept, for observing known (RV) exoplanets
- ***Planetscope Precursor*** is a near-term (Sept. 2007) flight experiment to estimate gondola-induced seeing contributions

Planetscope Collaborative Group:
Pin Chen, Wesley Traub, Michael Shao, John Trauger, Brian Kern, Bijan Nemati
Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, U.S.A.
Barth Netterfield
University of Toronto, Toronto, Ontario, Canada
Jeremy Kasdin
Princeton University, Princeton, NJ, U.S.A.

Top Level Science Requirement:

10^{-9} contrast for angular distances ≥ 0.1 arcsec

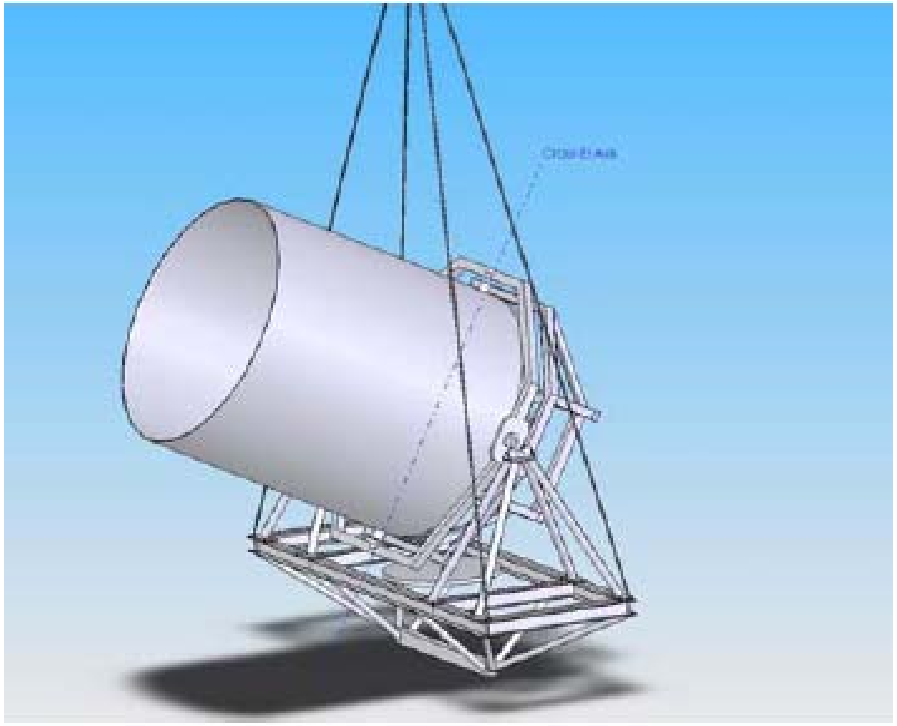
Significant sources of wavefront error		TPF-C				Planetscope				HST	
				Timescale				Timescale			
	unit	spec.	stability			spec.	stability			spec.	stability
Precision of DM settings	nm	0.014		>90 min		0.044		1 hr		NA	
Telescope pointing jitter											
body pointing of telescope	mas	35		Active (0.1Hz)		111		Active (0.1Hz)		3 - 5	
Star on the coronaraph mask (fine steering mirror)	mas	2.5		Active (10 Hz)		7.9		Active (10 Hz)		NA	
Surface of the primary mirror											
D/4 and larger	nm	8	1.6	Continuous		14	2.8	Continuous		9	unknown
D/50 to D/4 (polish and quilting artifacts)	nm	7	0.014	>90 min		22	0.044	1 hr		7	~ 0.01
Particulate contamination (dust and micro-meteor pits)		Level 750		Years		Level 750		8 hr		Level 750	
Coating reflectance uniformity (D/50 to D/4)		0.25%		Years		0.79%		years		unknown	
Surface quality of small optics	nm	1	0.014	>90 min		3	0.044			8	~0.01
Telescope alignment (separation of the SM and PM)	nm	1000		Continuous		1778		Continuous		2000	

Ref.: Trauger & Traub, *Nature* **446,** pp. 771-774, 2007

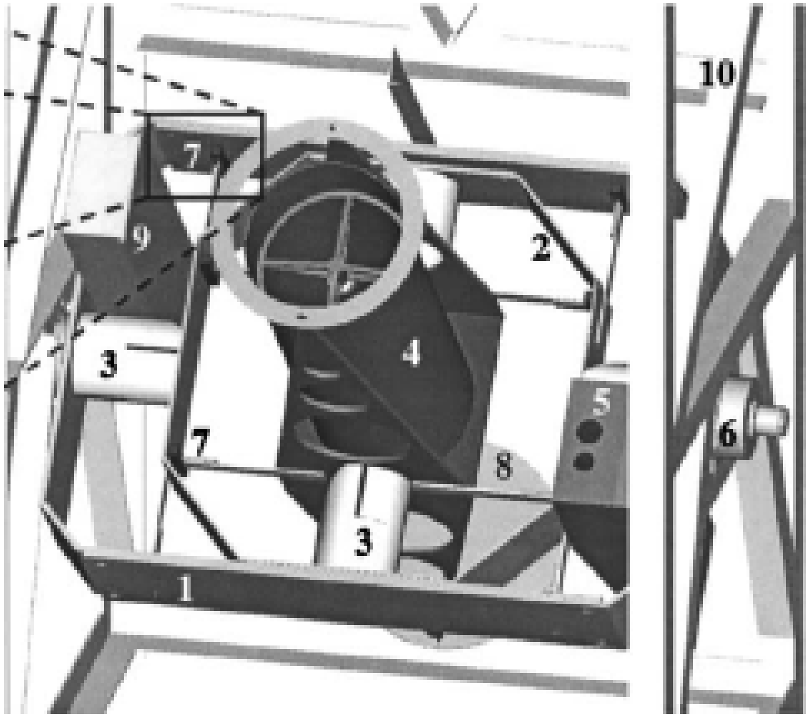
First, we need to know what contrast limit is set by the atmosphere at float altitude

Pointing Platform

2/3 axis frame, tip-tilt mirror, magnetically levitated bearings.



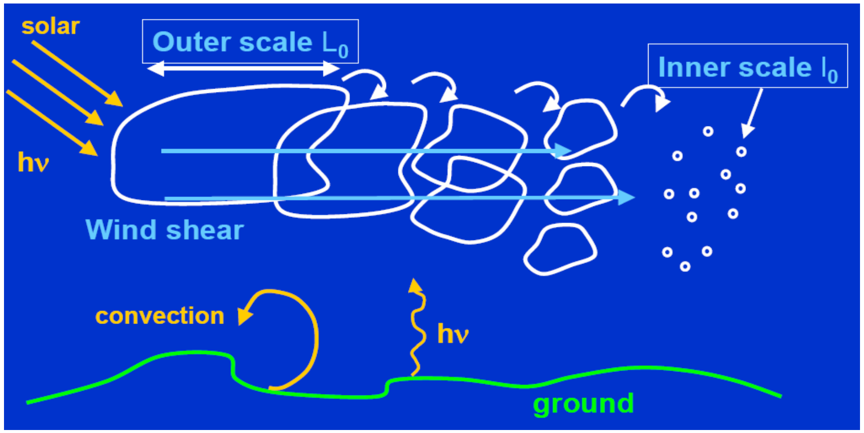
Planetscope concept



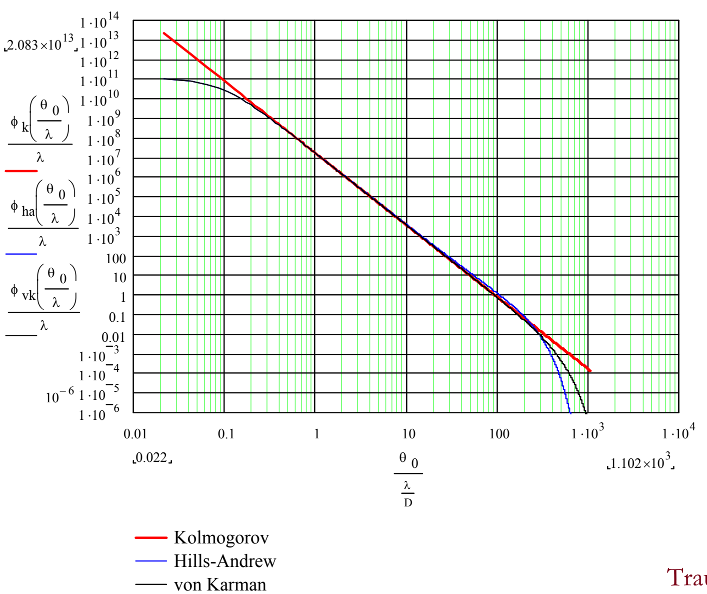
Solar Bolometric Imager
Bernasconi et al., Adv. Sp. Res. 2004

The Planetscope Precursor package will occupy the bottom 0.5x2x2 m^3 volume of the Solar Bolometric Imager gondola (Pietro Bernasconi, PI), and will incorporate a Mars-prototype anemometer from Ball Aerospace (Rich Dissly, mgr.) and Cornell Univ. (Don Banfield, PI).

Atmospheric Turbulence



A. Bouchez, "Introduction to Adaptive Optics."



Traub

Power spectra of phase aberrations, 3 models:

Kolmogorov

$${}^{K}\Xi_{\varphi}(f) = \frac{0.0229}{r_0^{5/3}} f^{-11/3}$$

von Karman

$${}^{VK}\Xi_{\varphi}(f) = \frac{0.0229}{r_0^{5/3}} (f^2 + \mathcal{L}_0^{-2})^{-11/6} \exp(-l_0^2 f^2$$

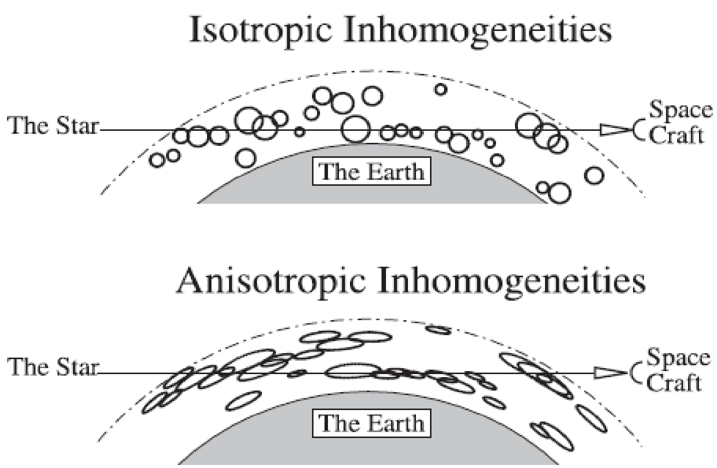
Hill-Andrews

$${}^{HA}\Xi_{\varphi}(f) = \frac{0.0229}{r_0^{5/3}} (f^2 + \mathcal{L}_0^{-2})^{-11/6}$$

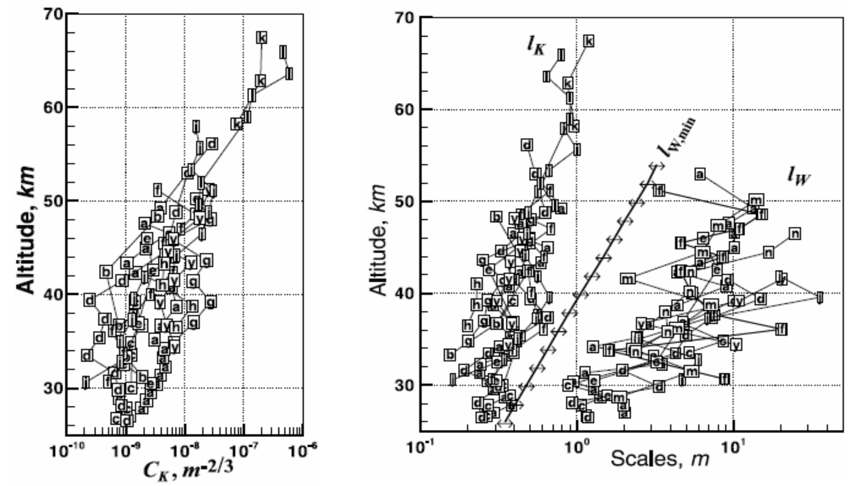
$$\times \left[1 + 3.43 f l_0 + 0.538 (f l_0)^{7/6}\right]$$

$$\times \exp(-3.625 f^2 l_0^2)$$

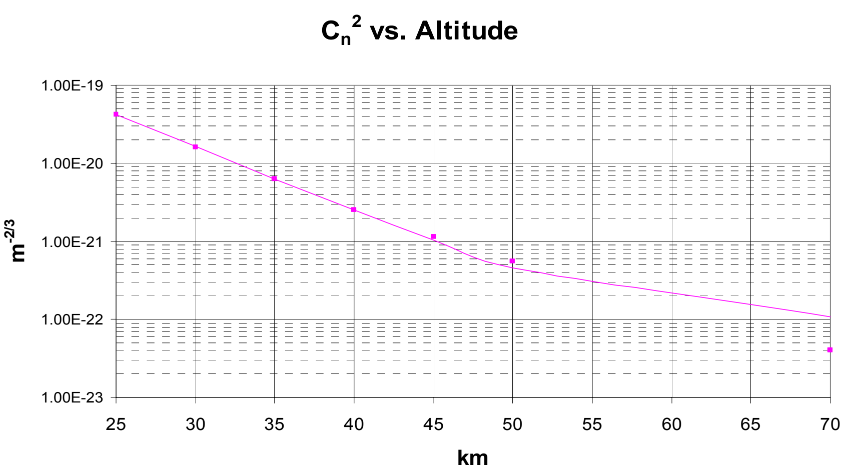
Scintillation from turbulence in the middle atmosphere



Gurvich & Brekhovskikh, *Waves in Random Media*, 2001



Gurvich & Chunchuzov, *JGR*, 2003



At 38-km altitude	Gnd-based obs.
r_0 = 57 m	~0.2 m
Inner scale = 2.7 m	~0.006 m
Outer = 69 m	~27 m

Contrast of speckles generated by atmosphere

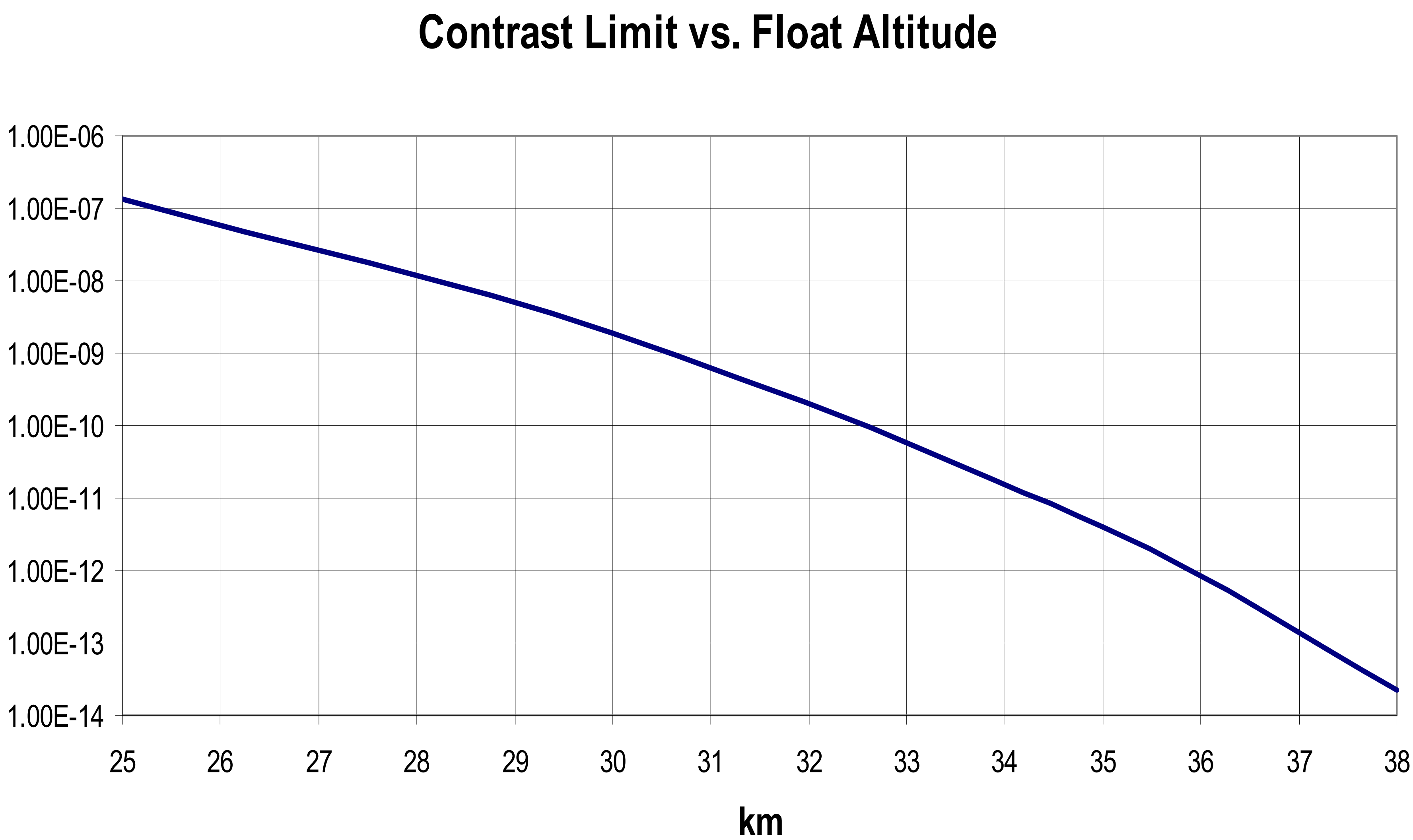
Operational parameters

- Float altitude: 38 km
- Observing wavelength: 550 nm
- Telescope aperture diameter: 2.5 m

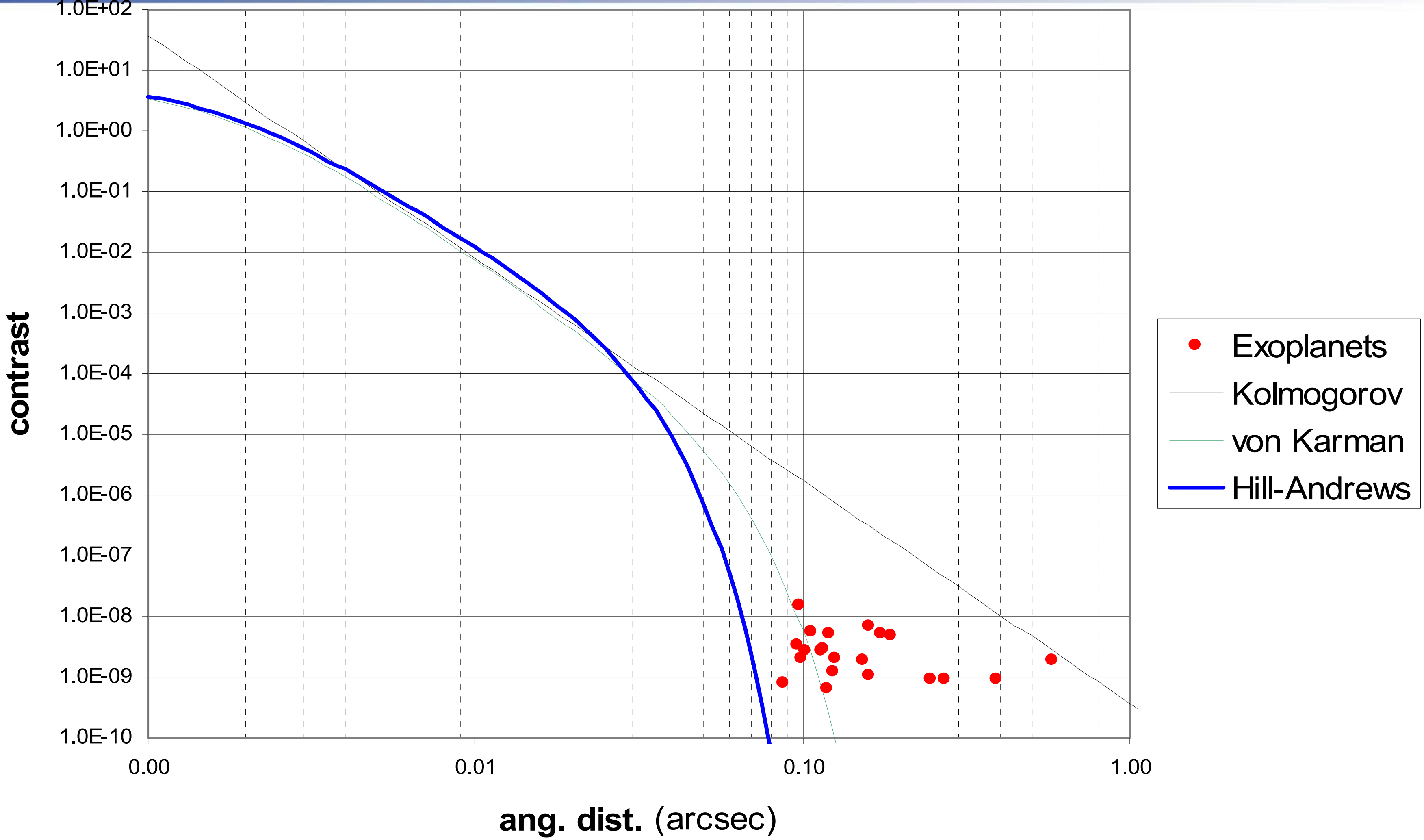
Calculation

- 2-dimensional power spectrum $\Xi(f)$ for index variations: Kolmogorov, von Karman, or Hill-Andrews model.
- For each spatial frequency f, integrate over a square of width λ/D to obtain magnitude of phase perturbation, h. D is the telescope's aperture diameter.
- Take into account of Fresnel propagation using formula in Guyon, *ApJ*, 2005.
- Speckle contrast level is $(\pi h/\lambda)^2$.

Contrast level dependence on altitude



Contrast Levels of Exoplanets & Atmospheric Speckles



Result: Speckles from the free atmosphere will not intrude on exoplanet images

Goal for Planetscope Precursor flight

- Assume that the free atmosphere is as described from the satellite observations and turbulence theory (previous charts).
- Address the question: are there additional optical path fluctuations near the gondola, as a result of convection induced by non-local temperature of the balloon or the gondola, the equivalent of astronomical ground-based "dome seeing"?
- Method: measure optical path fluctuations near the gondola, at level of few times 0.01/100 μm, using a commercial HP laser system (LSB = 0.01 μm) augmented by sub-LSB dithering of the optical path (using a piezo-driven mirror).
- Post-flight follow-up: lab measurements and theoretical calculations of gondola- or balloon-induced local seeing.

Conclusions

- Contrary to the ground-based case, the **inner scale of turbulence** (l_0) plays a crucial role at float altitudes for balloon-borne observatories.
- The middle-stratosphere appears to be an excellent setting for 10^{-9} contrast observations to directly characterize exo-Jupiters.
- Balloons can play an important role in exoplanet research, as a low-cost method of **improving TRL** values, and doing **new science** observations that can only be done above the atmosphere.

We thank *Olivier Guyon*, *Valery Zavorotny* and *Igor Chunchuzov* for technical discussions regarding stratospheric turbulence.