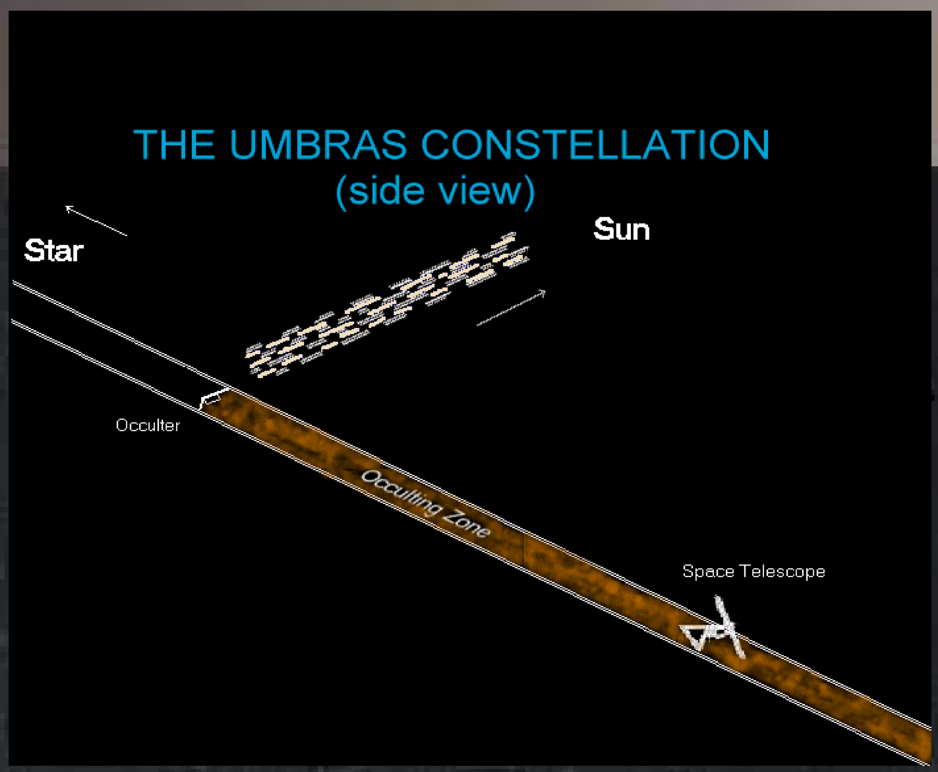
Free-flying Occulters for Use with Space Telescopes

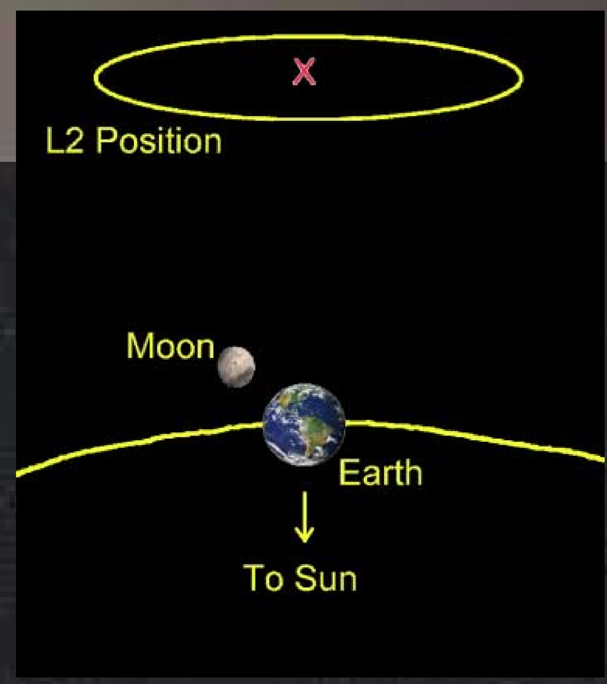
M. Kochte, I.J.E. Jordan, A. Schultz, F. Hamilton (CSC/STScI), F Bruhweiler, M.A. DiSanti (CUA), R.D. Burns, K. Carpenter, J.M. Hollis, J. Leitner, R.G. Lyon, S. Starin (NASA/GFSC), M.S. Fadali, M. Rodrigue (UNR), D.L. Skelton (OSC), H.M. Hart (CSC/JHU)

The diagram to the right shows the basic configuration of the occulter and telescope with respect to the sun and target star. The star, occulter, and telescope are in line, and the view is from above the plane containing these and the sun. The occulter moves to a position and undertakes formation control to block the light of the star from entering the telescope.



Free-flying occulters in association with space telescopes have been proposed for nearly four decades to detect and study extrasolar planets. External occulters reduce the magnitude differences between a planet and the host star; light scattered within the telescope is reduced resulting from fewer obstructions and optical surfaces; and any instrument aboard the telescope, including spectrometers, can be used to study extrasolar planets.

We conclude with a mission concept for an optimized optical 1-m space telescope with a small external occulter. Both craft could be launched from a single launch vehicle and placed in a 1-AU fall-away orbit, or at Earth-Sun L2. Jovian planets around stars within 10 parsecs could be studied, and a search for sub-Jovian planets around the nearest handful of stars could be performed. Approximately 80% of the telescope time would be available for projects not associated with the external occulter such as gravitational lensing and planetary transit surveys.



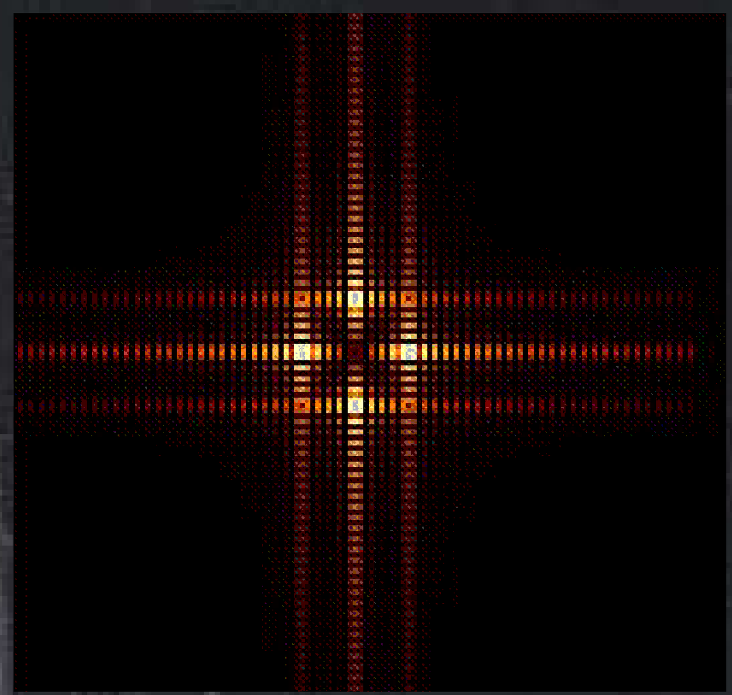
The diagram to the left illustrates the Earth-Sun L2 locus (Earth and Moon sizes are not to scale) which would be ideal for an occulting mission. The distance is great enough from large gravitating objects that differential shear will not disrupt exposures of length ~1000 seconds.

Table 1: Why not use an internal coronagraph?

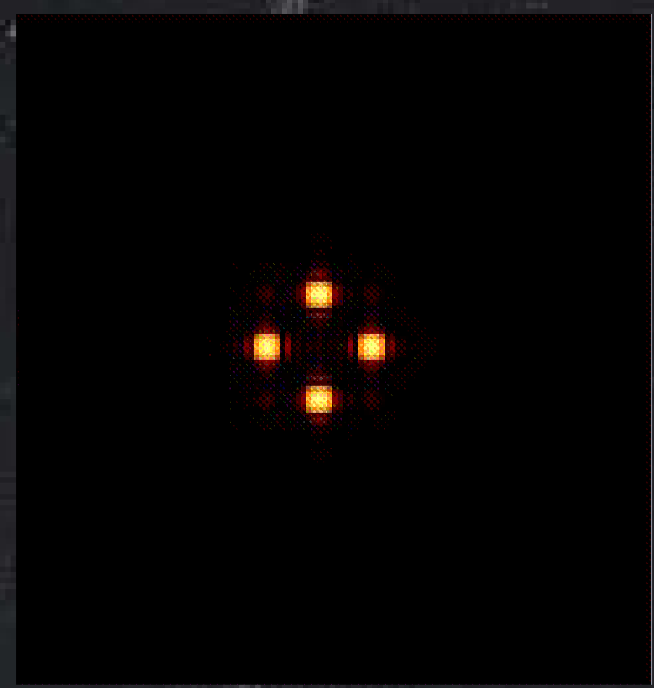
	Internal ("Classical") Coronagraph		External ("Paleolithic") Occulter	
	Pros	Cons	Pros	Cons
Internally Scattered Light?		Technically challenging for higher star light suppression.	None! No scattered light!	
Control of occulting spot position?		Has been an issue in previous coronagraphs.	Control is the name of the game!	
Usable with any telescope science instrument?		No	Yes	
Place target anywhere in image plane?		No	Yes	
Variable spot size (target optimized)?		No	Yes	
Optimum PSF redistribution for planet search?	Some designs can optimize.	All used to date are not optimally shaped.	Better than previous classical coronagraphs.	
Occulting Spot Shape	Can use arbitrary shape.	Design fixes shape.	Some shape change capability with occulter tilts.	Can't make occulter into some shapes.
Light Suppression factor	Some designs with higher theoretical contrast, but not demonstrated.		Better than previous generation of classical coronagraphs.	Highest suppression requires distant, large, slower occulters.
Exposure length limits.	Detector/background limited.			Limited near higher gravity gradients.
Separate Spacecraft?	Unnecessary.			At least telescope + occulter.
Operations	Well understood & straightforward.			More complex. Infeasible near Earth.
Cost	Coronagraph within telescope.	Microengineering costly for higher performance	Competitive for smaller occulters.	Usually always more for larger occulters.
Observation rate limits	Slew and acquisition time limited.			Must move hundreds to thousands of kilometres.
Lifetime	Life potentially unlimited.			Limited by s/c fuel and operations.

The table above shows contrasting pros and cons between internal coronagraphic instruments and external occulting craft.

Occulter Only

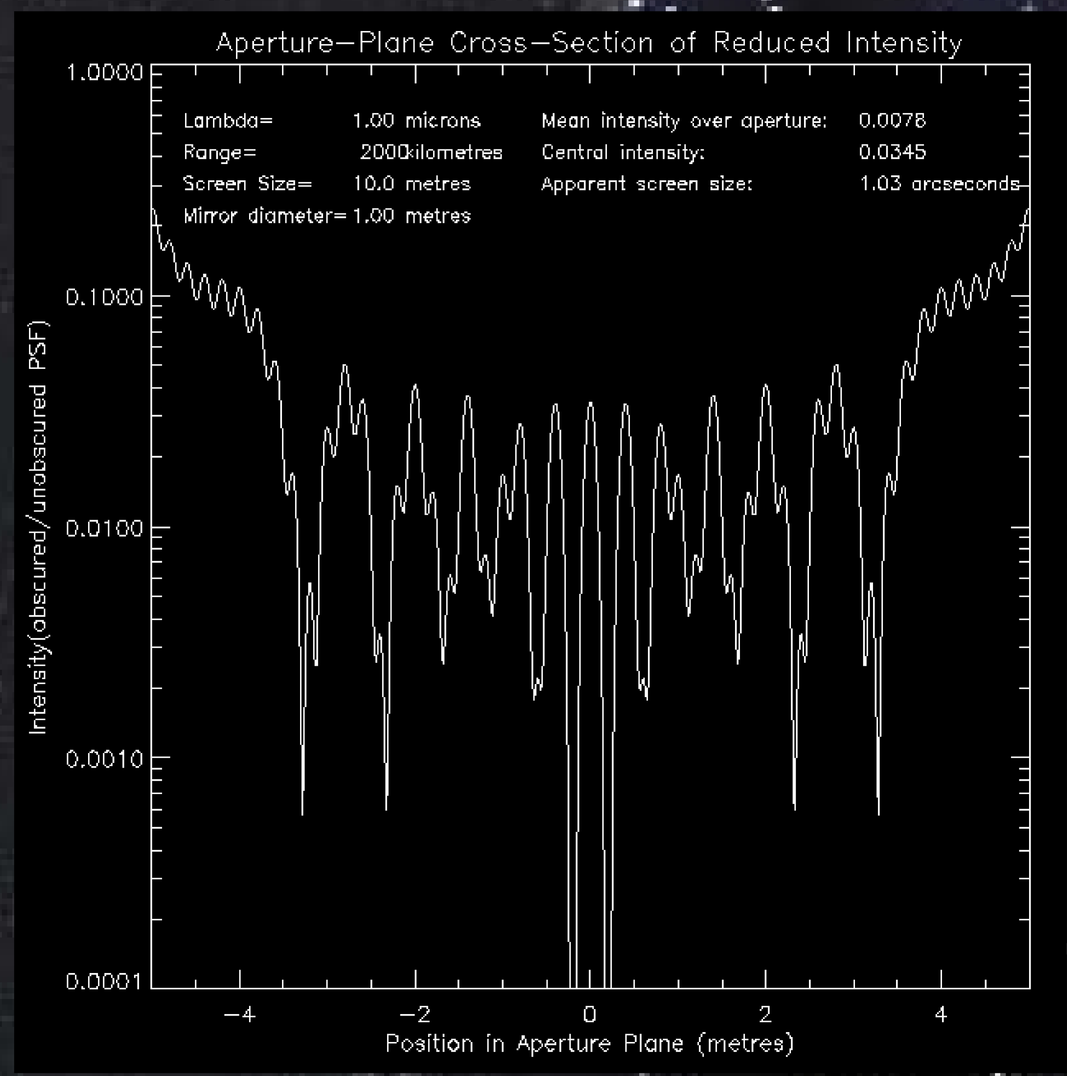


Occulter and Sonine Apodization

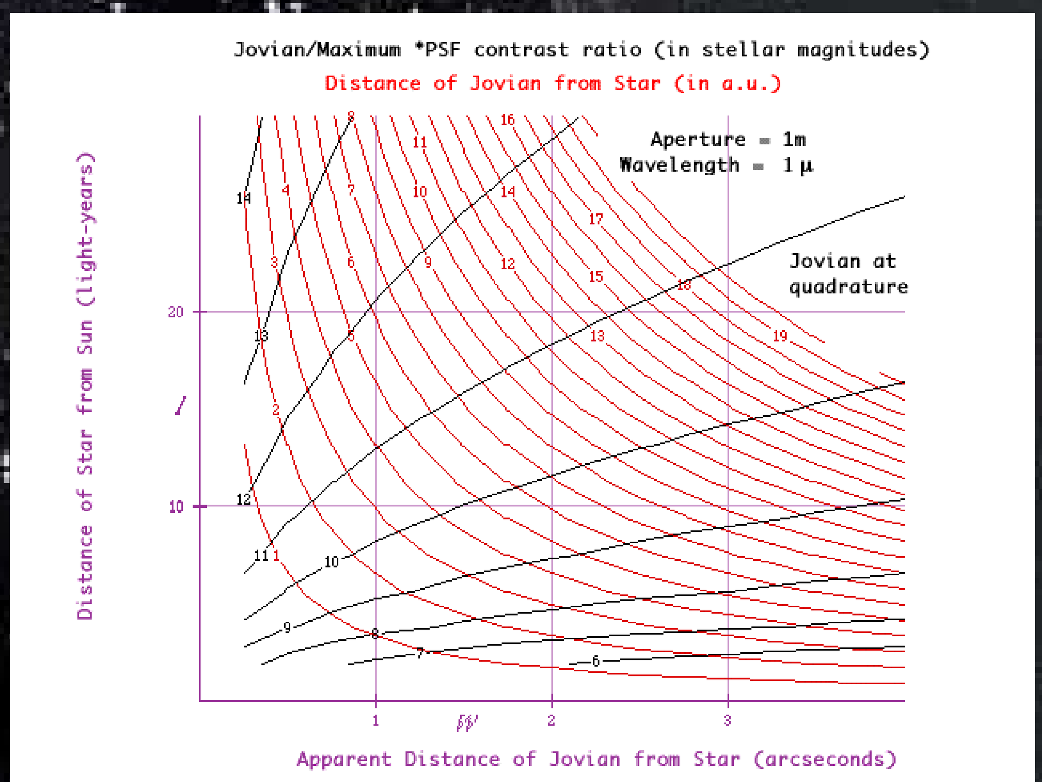


The figures above and below are presentations of a diffraction simulation run on HIVE at GSFC. The simulation is of a star viewed at 1-micron wavelength by a 1-metre square aperture, unoccluded telescope with a 10-metre square occulting screen separated by 1000 kilometres. In this simulation, the occulter appears about 1" across with $^{\lambda}/_{D}$~0.2".

In the 2-dimensional focal plane simulations above, the log stretched images show the appearance of the star using the occulter only (left) and an occulter plus 4th-order Sonine apodization (right). It can easily be seen that apodization strongly suppresses the diffraction spikes from the edge of the occulter and telescope.



Above is a cross-section for the simulation of the light reduction from a star observed at 1-micron wavelength behind the 10-metre square occulter in the aperture plane of the telescope. The distance used is representative of a likely operational scenario.



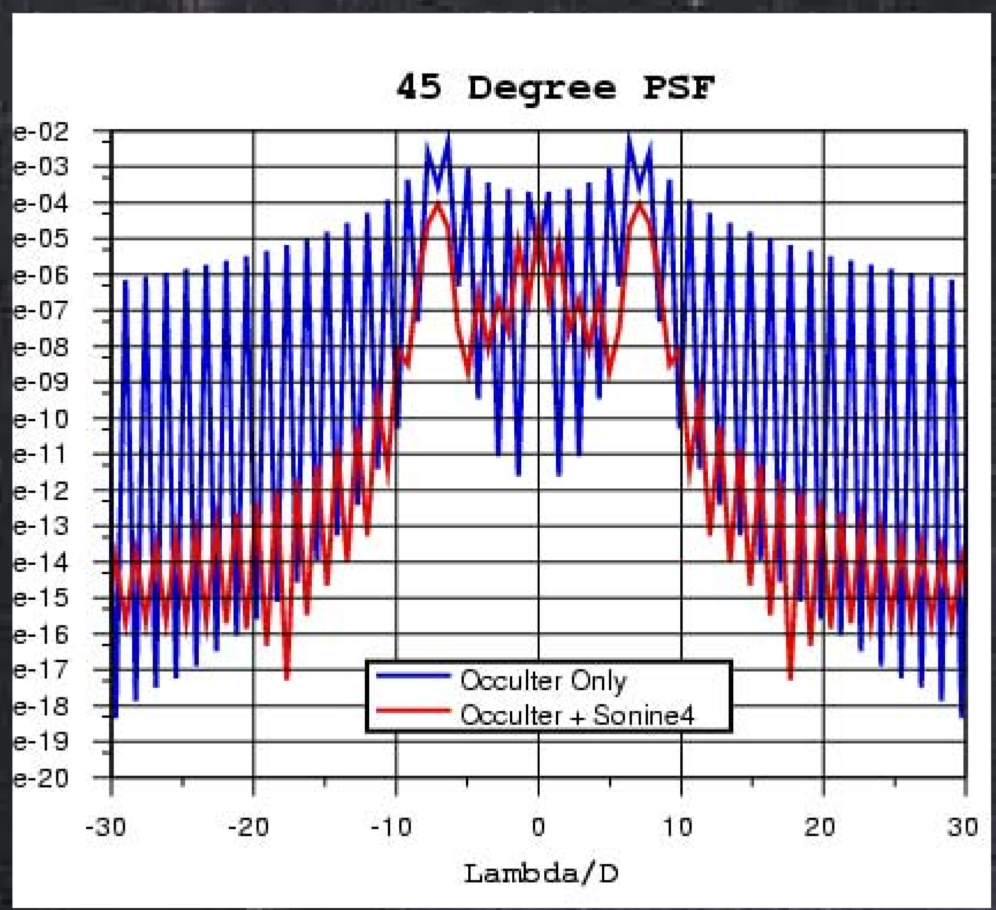
The graph above shows the difficulty of direct observation of extrasolar planets. Lines of constant contrast (black curves given in astronomical magnitudes) between a hypothetical extrasolar Jupiter-like planet, at greatest elongation, and the "ideal" PSF of a 1-metre, unoccluded telescope are plotted. The observational wavelength is at 1 micron.

Points in the plane further up (vertical axis in light-years) are representative of stars at larger distances from our sun. Points further to the right (horizontal axis given in arcseconds) represent planets which are at larger distances from the star they orbit.

The red curves show lines of constant separation (given in AU) between star and hypothetical extrasolar planet. For example, a planet at 20 light-years and 2-arcseconds from its star at greatest elongation would be just over 12 AU from the star.

Interpolating between curves, such an object would be about 11.3 astronomical magnitudes fainter than the stellar PSF.

Using an occulter and an apodized aperture telescope, (q.v. the cross-sections shown in the lower middle of this poster), ~ 10^6 suppression (15 astronomical magnitudes) of the PSF could be achieved at this location, making it brighter than the modified PSF and therefore a candidate for study.



In the graph to the left, a diagonal cross-section through the focal plane for the above simulated images is shown with the vertical scale relative to the peak unocculted intensity. Displayed in blue is the cross-section for the occulter only, while occulter-plus-apodization is shown in red. The two highest peaks in the cross section are at the corners of the occulting screen.

The occulter provides suppression of light entering the aperture, and therefore suppression of scattered light throughout the internal optical path. Although several orders of magnitude of light pollution suppression is provided in the field by the occulter, the greatest gain comes with combination of the occulter with apodization at the aperture. As can be seen, the simulation predicts many orders of magnitude of PSF suppression.

For more information, be sure to visit our webpage at: *http://www.stsci.edu/~jordan/umbras/*

The table below shows a selection of stars which could be likely candidates for a high contrast search for extrasolar planets. The table contains two types of candidates: nearby stars which could have relatively bright extrasolar planets (in white), and (in yellow) four stars having radial velocity extrasolar planet candidates.

The table shows the apparent brightness of select planets from our own solar system if they were placed in comparable orbits around those stars. Also given is the separation from the star at greatest elongation, and a theoretical contrast ratio. The contrast ratio is an ideal ratio (expressed in astronomical magnitudes) between the planet and the PSF of the unoccluded, unapodized 1-metre telescope.

The plot to the right shows the relative amounts of light blocked at the aperture of a 1-metre telescope for square occulters of varying sizes and separations. Although simulations show that the opaque occulter does not provide more than a few orders of magnitude suppression of the PSF, this is an important gain for scattered light internal to the telescope, and provides an important advantage for faint object studies when combined with other techniques, such as apodization

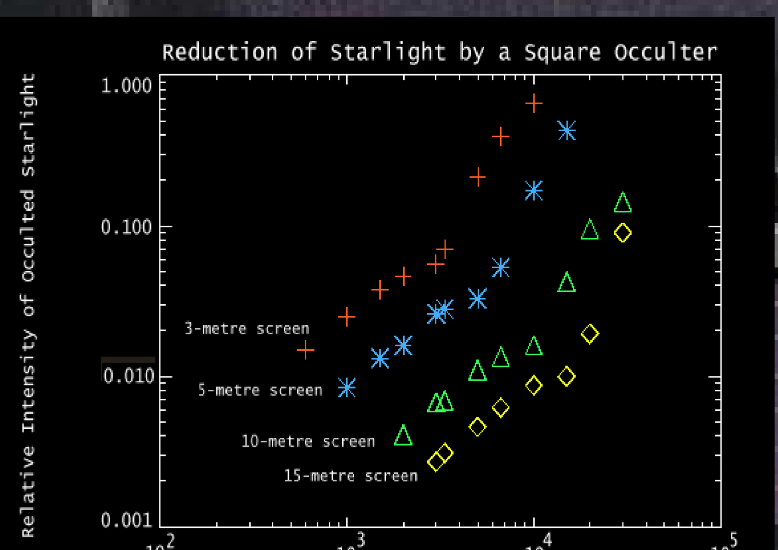


Table 1: Important Potential UMBRAS Candidates

Star				Earth-Moon			Jupiter			Saturn			Uranus		
Name	App m_V	Distance lt-yrs	Spectral Type	App m_V	Sep (m")	Contrast ratio	App m_V	Sep (m")	Contrast ratio	App m_V	Sep (")	Contrast ratio	App m_V	Sep (")	Contrast ratio
α Cen B	1.33	4.4	K1V	26.1	741.8	17.6	23.0	3857.1	4.9	24.4	7.1	5.1	28.1	14.2	8.0
α Cen A	-0.01	4.4	G2V	24.7	741.8	17.6	21.6	3857.1	4.9	23.0	7.1	5.1	26.8	14.2	8.0
Sirius A	-1.46	8.6	A1Vm	23.3	379.0	19.7	20.2	1970.9	7.1	21.6	3.6	7.3	25.3	7.3	10.2
18 ε Eri	3.73	10.5	K2V	28.5	310.6	20.4	25.4	1615.1	7.7	26.8	3.0	7.9	30.5	6.0	10.8
Procyon A	0.38	11.4	F5IV-V	25.1	285.8	20.7	22.0	1486.1	8.0	23.4	2.7	8.2	27.2	5.5	11.1
52 τ Ceti	3.49	11.9	G8V	28.2	274.0	20.8	25.1	1425.0	8.1	26.5	2.6	8.3	30.3	5.3	11.2
Altair	0.77	16.8	A7V	25.5	194.3	21.9	22.4	1010.6	9.3	23.8	1.9	9.5	27.6	3.7	12.3
24 η Cas A	3.44	19.4	G0V	28.2	167.9	22.4	25.1	873.1	9.7	26.5	1.6	9.9	30.2	3.2	12.8
δ Pav	3.6	19.9	G7IV	28.4	163.6	22.5	25.2	851.0	9.8	26.6	1.6	10.0	30.4	3.1	12.9
β Hyi	2.8	24.4	G1V-G2IV	27.6	133.7	23.1	24.4	695.3	10.5	25.8	1.3	10.7	29.6	2.6	13.5
Formalhaut	1.16	25.1	A3Va	25.9	130.0	23.2	22.8	676.1	10.6	24.2	1.2	10.8	28.0	2.5	13.6
Vega	0.03	25.3	A0Va	24.8	128.9	23.3	21.7	670.1	10.6	23.1	1.2	10.8	26.8	2.5	13.7
π^3 Ori	3.19	26.2	F6V	27.9	124.5	23.4	24.8	647.6	10.7	26.2	1.2	10.9	30.0	2.4	13.8
44 χ Dra	3.55	26.3	F7V	28.3	124.0	23.4	25.2	645.1	10.8	26.6	1.2	11.0	30.3	2.4	13.9
86 μ Her A	3.42	27.4	G5IV	28.2	119.0	23.6	25.0	618.8	10.9	26.5	1.1	11.1	30.2	2.3	14.0
13 γ Lep	3.59	29.3	F7V	28.3	111.4	23.8	25.2	579.5	11.1	26.6	1.1	11.3	30.4	2.1	14.2
23 δ Eri	3.54	29.5	K0IV	28.3	110.5	23.8	25.2	574.7	11.2	26.6	1.1	11.4	30.3	2.1	14.2
53 ξ UMa B	4.87	25.1	F8.5V	29.6	129.9	23.3	26.5	675.3	10.6	27.9	1.2	10.8	31.7	2.5	13.7
4 τ Boo	4.5	50.9	F6IV	29.3	64.1	25.6	26.1	333.3	12.9	27.5	0.6	13.1	31.3	1.2	16.0
ε Retic	4.44	59.5		29.2	54.8	26.1	26.1	285.0	13.5	27.5	0.5	13.6	31.2	1.1	16.5
Aldebaran	0.87	65.1	K5III	25.6	50.1	26.4	22.5	260.3	13.7	23.9	0.5	13.9	27.7	1.0	16.8

We would like to thank Ed Rowles for creating the background image, and Dan Schroeder of Beloit College for supplying software to create aperture plane cross-sections. And thanks to mom and dad for allowing me to go out in the middle of the night with my telescope to look at the stars.