Necessary conditions for capturing features on Uranus.

1- Requested conditions:

Data are extracted from the publication
"Observing the moon, planets and comets"
By Clark R. Chapman and Dale P. Cruikshank.

1.1- Uranus surface brightness (B)

Albedo: 0.509 Surface brightness: 54 cd/m2
Saturn albedo: 0.461 Surface brightness: 180 cd/m2

Sky transparency: µ
Minimal visual sky transparency: usually m: 4.0 to 5.0 well accessible,
Filter in use (usually: W82A, W8, W12, W.F.): coefft.>0.80,
Clean optics: coefft.>0.80 (including refelectivity and CO optical).

Britghtness through the telescope: B+ = D2.Bf / d2.M2 or 25.D2.µ.B / M2
D: aperture (here 8" or 200mm),
d: eye pupil diameter,
Bf: brightness at scope exit Bf = µ.B
m = 4.0 µ = 0.05 Tr (sky) 0.4 to 0.8
m = 5.0 µ = 0.25

B+ for D 8" M = 360x µ = 0.05 Bf = 2.5 cd/m2
d = 0.55mm or 0.022" µ = 0.25 Bf = 12.5 cd/m2

B+ = 0.15cd/m2 D 8" M 360x m: 5.0
B+ = 0.03 cd/m2 D 8" M 360x m: 4.0

Needed optimum magnification P = M/D (magnification per inch aperture) or SQR(25.µ.B/B+)

1.2- **Optimal conditions**:

For 8" aperture 360x magnification m:5.0:
Brightness at the eyepiece: 0.15 cd/m2
Brightness of planet: 50 cd/m2
Requested magnification per inch: 45.6x therefore 365x for 8"
Mesopic vision: Lighting level from 0.001 cd/m2 until 10 cd/m2
FOR A STANDARD EYE.

Observation of Uranus features mainly for 619nm area.
Represents about 40% of the max eye sensitivity for a mesopic vision
So the planet brightness at the eyepiece of 0.15 cd/m2 becomes 0.06 cd/m2.
The use of a W8 filter represents the ratio of the 40% under eye senvitivity curve.
0.06 cd/m2 level preserve well the mesopic vision abilities with the scope conditions not affected.

1.3- <u>Contrast perception:</u>

a- Uranus exhibits clouds on a tiny 3.60” disk size.
Width of the cloud bands, say: about 1.0”

1.0” x 360 (magnification) = 360” or 6’ arc apparent size at eyepiece,
Therefore 10 cycles/ °,

The standard eye contrast sensitivity function at 10 cycles/°:
- mesopic vision: 1-2%
- photopic vision: 0.6-0.7%

for the planet on subject.

b- Scope effect:
- Strehl ratio: contrast through scope = actual contrast of feature x strehl ratio

Strehl 99% not affecting results.

c- CO, central obstruction:
For a RC200 with CO 35 and 42%, resolution limit remains 0.60”,
FTM curves exhibit the fact that contrast are kept in comparison with a perfect scope of no CO near the ultimate resolution ability (right part of the curve).

d- Maximisation of the magnification for the contrast perception at low light levels should be at about 10 cd/m2,
but performance (contrast versus feature size) can be kept with the proper increased magnification.
8” scope with 400x
M: 5.0, clean optics, µ: 0.25
Seeing good to excellent (Danjon scale 10/10 to 7-8/10),

Contrast through the 8” scope
For features as lines: c+ = c.(w/(w+5.6/D))
w: line width
c: actual feature contrast
c+: observed contrast

for 1.0” width line, c = 1%, c+ = 0.59%
for 1.2” width line, c = 1%, c+ = 0.63%

for a 12” scope and c = 1% c+ = 0.68%
for a 16” scope and c = 1% c+ = 0.74%
for a 40” scope and c = 1% c+ = 0.88%

e- Optimum observational conditions including the seeing for contrast perception:
- 10” scope perfect, µ 0.1, m 4.5, M 540x seeing 1/3” (Danjon 7-8/10),
  M 280x seeing 1” (Danjon 3-4/10),
- 16” scope perfect, µ 0.1, m 4.5, M 710x seeing 1/3” (Danjon 7-8/10),
  M 325x seeing 1” (Danjon 3/10),
- 8” scope, 360x seeing <1/3” (Danjon 9-10/10)

Apparent size at the eyepiece about 22’ arc, surface apparent brightness 0.15-0.20 cd/m2
The contrast perception can be 1.50%.

- 8” scope, 400x seeing < 1/3”,
Apparent size 24’ arc: the contrast perception can 1.30%.

2- <u>Tests performed:</u>

2.1- Distanced targets:
Creation of targets.
Software word can ceate features until 5% contrast level.

Disk size at 1000m distance: 17mm
a- Background color of the disk: light grey (10% contrast with a whitish paper)
b- Feature levelled at 15%
See the specimen.
c- Same specimen with 2-3% contrast level.
d- Lighting conditions of the target:
Day light with no sun,
Twiglight,
Moon light (full moon as 0.5-1.0 Lux lighting).
e- Seeing evaluation:
An artificial star was installed just near the target panel.
Worked well in twilight and moon light.
f- Results:

	C=5%	C=2-3%	M	
L110	Y.Y.Y Y.Y.N	Y.Y.N Y.(Y).(N)	308x	apochromat
L150	Y.Y.Y Y.Y.Y	Y.Y.Y Y.Y.(Y)	313_350x	achromat
RC200	Y.Y.Y Y.Y.Y	Y.Y.Y Y.Y.Y	360x	Ritchey
Seeing	10/10 7-8/10	10/10 7-8/10	S	

Results were aleatory when S < 7/10 continuous.
Answers formatted as: Y.Y.N (daylight, twilight, moon light), Y: yes pass, N: not pass.

2.2- Personnal eye evaluation:
Performed at a famous Engineering Body for oil and gas activities.
Divers can be tested under US standards.
The tests were conducted in B G R colors, low light levels, FTM grids for some.
Results:
50” resolution ability at few lux illumination of examined targets of very low contrast levels (<5%).

3- Works performed:
3.1- Observations since the 2009 opposition,
Results published at the Japanese Alpo and the BAA Uranus section
http://alpo-j.asahikawa-med.ac.jp/Latest/Uranus.htm
The results shows some variabilities of the planet (especially last opposition 2010-2011)
- slight contrast variabilities,
- cloud activity accessible in visual fields.

3.2- Uranus requested conditions:

The spectrum of Uranus exhibits absorption rays in visual area (especially at the 619nm), but other lighter rays are existing in other visual fields.
Rather than the direct visual observations, some US amateur observers (Schmude, Mellilo, …) suggested the follow-up of the activity of Uranus though the collection of spectrum (absorption rays variation).
Some polarimetric observations for investigation should be undertaken also, being a not negligeable parameter at priori (having owned a C8 with a light polarimetric effect, that may false some data).
Think that the features collection remains accessible directly visually but to-day at the margin of a 150-200mm scope aperture.
The pertinence of the result is:

- lightly improved with the aperture increase, the seeing parameter becoming the more influent parameter quickly,
- at the best when the global transparency and transmission are at the best possible,
- at the best when the scope strehl ratio is high (>95% actual and global),
- at the best when the exit pupil diameter is fixed to 0.50-0.55mm, where the mesopic vision potential is at the best conditions.

4- **Conclusion**:

The present study may involve a good pertinence and reliability of the given results by:

- the respected best mesopic vision conditions,
- the results get on distanced targets,
- the personnal vision control.

If visual observations are faced to difficult conditions, what is sure is

- average trained observers cannot do something fruitfully,
- imagers are also faced by these observational conditions, features being washed quickly by the site observation condition and the lack of scope quality (as a preliminary approach).

Stanislas Maksymowicz
BAA member
Uranus observer.

Annexes:

- article from www.telescope-optics.net/eye_spectral_response.htm,
- fig.1 from the Chapman and Cruikshank publication
- tablesheet from the Chapman and Cruikshank publication, sheet 182-183,
- table 2 from the Chapman and Cruikshank publication, sheet 145,
- table 3 from the Chapman and Cruikshank publication, sheet 146,
- table 4 from the Chapman and Cruikshank publication, sheet 152.

Table 1. The Planets and their Surface Brightnesses

Planet	Radius R (A.U.)	Geometric Albedo, p_V	Phase Angle, i	Phase Factor	Effective Albedo, A_V	Brightness B (cd/m^2)	Brightness Ratio Perihelion/Aphelion
Mercury	0.39	0.100	90°	0.17	0.017	4,200	2.3
			50	0.32	0.032	7,700	
			130	0.072	0.0072	1,800	
Venus	0.72	0.586	90°	0.48	0.28	20,000	
			50	0.73	0.43	29,000	
			130	0.45	0.26	18,000	
Moon	1.00	0.115	0°	1.	0.115	4,100	
			90	0.17	0.020	700	
			50	0.34	0.039	1,400	
			130	0.084	0.0095	340	
Mars	1.52	0.154	0°	1.0	0.154	2,350	1.5
			47	0.62	0.095	1,400	
Jupiter	5.20	0.445				585	1.2
Saturn	9.58	0.461				180	
Uranus	19.14	0.565				54	
Neptune	30.2	0.509				20	

(Note: Jupiter's satellites I and II are about twice as bright as Jupiter, III about equal, and IV about half as bright. Also, it is of interest to note that a typical brightness for the daylit sky is 8,000 cd/m^2.)

Table 2. Values for the Total Transmission Coefficient μ as a Function of T_r and $\mu_r\mu_t$

T + μ, ℓte 0,5

Transparency T_r	$\mu_r\mu_t = 0.8$	$\mu_r\mu_t = 0.6$	$\mu_r\mu_t = 0.4$
6.00	0.64	0.5	0.3
5.75	0.5	0.4	0.25
5.5	0.4	0.3	0.2
5.25	0.3	0.24	0.16
5.0	0.25	0.2	0.13
4.75	0.2	0.15	0.1
4.5	0.16	0.12	0.08
4.25	0.13	0.095	0.06
4.0	0.1	0.075	0.05
3.75	0.08	0.06	0.04
3.5	0.06	0.05	0.03
3.25	0.05	0.04	0.025
3.0	0.04	0.03	0.02
2.75	0.03	0.024	0.016
2.5	0.025	0.02	0.013
2.25	0.02	0.015	0.01
2.0	0.016	0.012	0.008
1.0	0.006	0.005	0.003
0.0	0.0025	0.002	0.0013

$$P = M/D = \sqrt{\frac{25\,\mu B}{B^{+}}} \quad . \qquad (18)$$

Solutions to this equation are presented in Table 3 using the values for B given in Table 1. The observer should select μ from Table 2, find it in Table 3 below the desired surface brightness in cd/m^2, and read across for the approximate magnification per inch of aperture for the planet in question. The table should be useful not only for optimizing contrast perception as discussed in the next section but also

Table 3. Magnification per Inch of Aperture for Given Surface Brightnesses

Transmission Coefficient
μ as found in Table 2.

Surface Brightness (cd/m^2) 0.1	1	10	100	1000	Mercury i= 90°	Mercury 50°	Mercury 130°	Venus 90°	Venus 50°	Venus 130°	Moon 0°	Moon 90°	Moon 50°	Moon 130°	Mars 0°	Mars 47°	Jupiter	Saturn	Uranus	Neptune
.6																			90	55
.5																			82	50
.4																		130	73	45
.3																		120	63	39
.2														130				95	52	32
.1												130		92			120	67	37	22
.08												120		82			110	60	33	20
.06	.6											102	150	72		150	94	52	28	17
.05	.5											93	130	65		130	85	47	26	16
.04	.4											84	120	58	150	120	77	42	23	14
.03	.3											72	105	51	130	105	66	37	20	12
.02	.2						95				140	59	84	41	110	84	54	30	16	10
.01	.1						67				101	42	59	29	77	59	38	21	12	7
.008	.08				92		60				91	37	53	26	69	53	34	19	10	6
.006	.06	.6			79		52				78	33	46	23	59	46	30	16	9	5
.005	.05	.5			72	98	47			150	71	30	42	20	54	42	27	15	8	5
.004	.04	.4			65	88	42	140		130	64	26	37	18	48	37	24	13	7	
.003	.03	.3			56	76	37	120	150	120	56	23	32	16	42	32	21	12	6	
.002	.02	.2			46	62	30	100	120	95	45	19	26	13	34	26	17	10	5	
.001	.01	.1			32	44	21	70	85	67	32	13	19	9	24	19	12	7		
	.008	.08			29	39	19	63	76	60	29	12	17	8	22	17	11	6		
	.006	.06	.6		25	34	16	55	66	52	25	10	115	7	19	15	9	5		
	.005	.05	.5		23	30	15	50	60	47	23	9	13	7	17	13	9			
	.004	.04	.4		20	28	13	45	54	42	20	8	12	6	15	12	8			
	.003	.03	.3		18	24	12	39	47	37	18	7	10	5	13	10	7			
	.002	.02	.2		14	19	10	32	38	30	14	6	8		11	8	5			
	.001	.01	.1		10	14	7	22	27	21	10		6		8	6				
		.008	.08		9	12	6	20	24	19	9		5		7	5				
		.006	.06	.6	8	11	5	17	21	16	8				6					
		.005	.05	.5	7	10		16	12	15	7				5					
		.004	.04	.4	7	9		14	17	13	6									
		.003	.03	.3	6	8		12	15	12	6									
		.002	.02	.2		6		10	12	10										
		.001	.01	.1				7	9	7										
			.008	.08				6	8	6										
			.006	.06				5	7	5										
			.005	.05				5	6											
			.004	.04					5											
0.1	1	10	100	1000	Mercury			Venus			Moon				Mars		J	S	U	N

3. Best Magnifications. Fig. 2, adapted from Ref. , is very useful for determining the optimum contrast perception. On this figure contrast is plotted against image size (in minutes of arc) and against surface brightness (in cd/m^2). If during any observation the size of the planetary features being observed and the apparent surface brightness of the planet is such that when plotted on Fig. 2 the point falls below the slanted line, than the contrast perception can be improved by increasing the magnification, so long as the point does not cross into the part of the graph above the slanted line. Similarly, if it falls above the line, the magnification should be reduced.

Table 4. Rough Guide for Magnifications Yielding Optimum Contrast Perception (With Excellent Observing Conditions and Clean Optics).

Nature of Planetary Detail	Telescope Aperture: 4"	8"	16"
Mercury (general features)	(600x)	800x	1000x
Venus ($i = 90^\circ$, large diffuse features)	200x	200x	250x
Venus ($i = 90^\circ$, finest details)	(700x)	(1200x)	(2500x)
Moon (quarter phase, large areas about 20 miles across)	120x	130x	150x
Moon (quarter phase, finest details)	400x	800x	1500x
Mars (general features near opposition)	500x	600x	800x
Mars (finest details)	(700x)	(1200x)	(2000x)
Jupiter (average belts and zones)	200x	300x	450x
Jupiter (finest details)	450x	900x	(1900x)
Saturn (average belts and zones)	200x	240x	320x
Saturn (finest details)	500x	800x	1100x
Uranus	300x	400x	1200x

(Note: In general for average observing conditions ($D^+ = 4$ inches, $\mu = 0.1$), divide all suggested magnifications by about 2, except divide by 3 for large telescopes when used on Mercury, Uranus, and for finest details on the moon and other planets.)

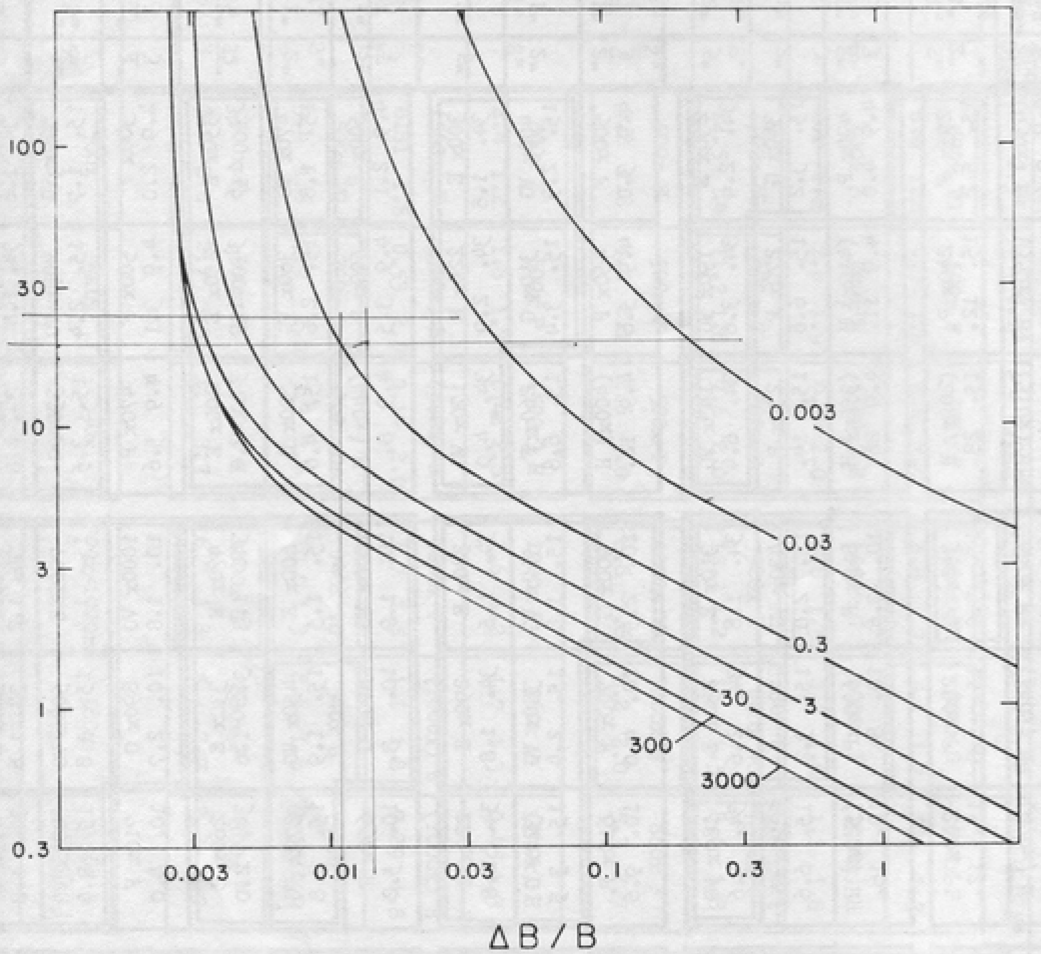

fig. 1

Y axis: disk size in (‘) arc
X axis: contrast image
Curves: for surface brightness image in cd/m2

Planet and Surface Brightness	R_s Seeing	Spot Diam.	D = 5 inches, R_t = 1.1" μ = 0.5	 μ = 0.1	 μ = 0.025	D = 10 inches, R_t = 0.56" μ = 0.5	 μ = 0.1	 μ = 0.025	D = 16 inches, R_t = 0.35" μ = 0.5	 μ = 0.1	 μ =0.025	NOTES
MARS 2500 $\frac{cd}{m^2}$	<2"	5"	400x E 34. 1.6	275x E 34. 1.8	230x E 34. 2.8	520x E 34. 1.2	360x E 34. 1.6	275x E 34. 1.8	660x E 34. 1.2	450x E 34. 1.4	335x E 34. 1.7	
	1"	2"	500x VG 15. 1.7	400x VG 15. 2.4	330x G 15. 3.5	700x E 15. 1.4	500x VG 15. 1.8	400x VG 15. 2.4	840x E 15. 1.3	590x VG 15. 1.6	450x VG 15. 1.8	2
also nearly full moon	$\frac{1}{3}$"	$\frac{2}{3}$"	500x F 4.9 2.0	500x F 4.9 3.1	470x P 4.9 5.6	1000x VG 10. 1.8	890x G 10. 2.7	710x F 10. 4.0	1600x VG 15. 1.7	1230x VG 15. 2.2	960x G 15. 3.4	2
MARS 1500 $\frac{cd}{m^2}$	<2"	5"	350x E 34. 1.6	250x E 34. 1.9	200x E 34. 3.0	470x E 34. 1.3	330x E 34. 1.6	260x E 34. 2.0	550x E 34. 1.2	400x E 34. 1.5	310x E 34. 1.7	
	1"	2"	470x VG 15. 1.8	360x VG 15. 2.6	300x G 15. 4.0	600x E 15. 1.5	450x VG 15. 1.9	370x VG 15. 2.8	740x E 15. 1.3	550x VG 15. 1.7	415x VG 15. 2.0	2
also gibbous moon	$\frac{1}{3}$"	$\frac{2}{3}$"	500x F 4.9 2.1	500x P 4.9 3.5	(440x) H 4.9 8.	1000x VG 10. 1.9	800x G 10. 3.	650x F 10. 5.2	1470x VG 15. 1.8	1140x VG 15. 2.5	890x G 15. 3.9	2, 3
JUPITER 585 $\frac{cd}{m^2}$	<2"	5"	300x E 34. 1.8	220x E 34. 2.9	170x VG 34. 4.0	380x E 34. 1.5	290x E 34. 1.8	220x E 34. 2.6	450x E 34. 1.4	330x E 34. 1.6	250x E 34. 2.0	1
	1"	2"	400x VG 15. 2.3	310x G 15. 3.4	260x F 15. 6.8	510x VG 15. 1.8	380x VG 15. 2.4	320x G 15. 3.5	620x E 15. 1.5	460x VG 15. 1.8	360x VG 15. 2.7	1,2
	$\frac{1}{3}$"	$\frac{2}{3}$"	500x F 4.9 3.0	450x P 4.9 5.6	(400x) H 4.9 12.	900x G 10. 2.5	700x F 10. 4.0	610x P 10. 9.6	1200x VG 15. 2.1	920x G 15. 3.4	800x F 15. 6.4	1, 2,4
SATURN 180 $\frac{cd}{m^2}$	<2"	5"	250x E 34. 2.4	190x VG 34. 3.6	145x VG 34. 6.4	310x E 34. 1.8	230x E 34. 2.6	180x VG 34. 3.6	360x E 34. 1.5	260x E 34. 1.9	220x E 34. 2.9	
	1"	2"	340x G 15. 3.2	270x F 15. 6.6	230x P 15. 14.	430x VG 15. 2.0	320x G 15. 3.2	270x F 15. 6.6	500x VG 15. 1.8	375x VG 15. 2.8	300x G 15. 3.8	
	$\frac{1}{3}$"	$\frac{2}{3}$"	490x P 4.9 4.0	(410x) H 4.9 11.	(350x) H 4.9 26.	810x F 10. 3.6	630x P 10. 8.	(520x) H 10. 16.	1050x G 15. 3.0	830x F 15. 6.	700x P 15. 12.	5
URANUS 54 cd/m^2	1"	2"	275x F 15. 5.2	240x P 15. 12.	(200x) H 15. 28.	350x VG 15. 3.0	280x F 15. 6.8	240x P 15. 12.	400x VG 15. 2.3	325x G 15. 3.6	265x F 15. 8.	
	$\frac{1}{3}$"	$\frac{2}{3}$"	(430x) H 4.9 9.6	(350x) H 4.9 24.	(310x) H 4.9 60.	640x F 10. 6.0	(540x) H 10. 16.	(470x) H 10. 32.	860x F 15. 5.2	710x P 15. 11.2	(600x) H 15. 25.	

MERCURY 8000 cd/m²	Sky Brightness 8000 cd/m²	1"	2"	500x VG 6.4 1.2	500x F 4.7 1.6	500x P 1.5 1.7	1000x VG 6.8 1.2	800x G 5.1 1.2	760x P 1.6 1.3	1150x VG 6.8 1.2	990x G 5.1 1.2	930x P 1.6 1.2
		1/3"	2/3"	500x P 2.1 1.8	500x P 1.6 1.9	(500x) H 0.5 2.0	1000x G 4.6 1.5	1000x F 3.3 1.6	(1000x) H 1.1 1.8	1600x VG 6.9 1.3	1600x G 4.9 1.6	1600x P 1.6 1.6
	Sky Brightness 800 cd/m²	1"	2"	500x VG 12.5 1.4	490x VG 11.7 1.8	390x G 7.6 2.0	920x E 13.3 1.2	640x VG 12.5 1.5	540x G 8.1 1.8	980x E 13.3 1.2	830x E 12.5 1.2	640x VG 8.1 1.5
		1/3"	2/3"	500x F 4.2 1.8	500x F 4.0 2.1	500x P 2.6 3.0	1000x VG 8.6 1.6	1000x G 8.2 2.0	880x F 5.3 2.7	1600x VG 12.6 1.5	1430x VG 12.0 1.9	1140x G 7.8 2.2
MERCURY 2000 cd/m²	Sky Brightness 8000 cd/m²	1"	2"	500x F 2.4 1.2	500x P 1.6 1.7	(500x) H 0.42 2.0	1000x F 2.6 1.2	760x P 1.7 1.3	(740x) H 0.45 1.3	1180x F 2.6 1.2	930x P 1.7 1.2	(870x) H 0.45 1.2
		1/3"	2/3"	(500x) H 0.81 1.8	(500x) H 0.53 2.0	(500x) H 0.14 2.0	1000x P 1.7 1.5	(1000x) H 1.1 1.8	(1000x) H 0.29 1.8	1600x F 2.4 1.4	1600x P 1.6 1.6	(1600x) H 0.42 1.7
	Sky Brightness 800 cd/m²	1"	2"	500x VG 9.4 1.6	390x G 7.9 2.0	340x P 3.3 2.4	740x VG 10.0 1.3	540x G 8.4 1.8	500x F 3.5 1.9	890x VG 10.0 1.2	640x VG 8.4 1.5	600x F 3.5 1.6
		1/3"	2/3"	500x F 3.2 2.0	500x P 2.7 3.0	(500x) H 1.1 3.3	1000x G 6.7 1.8	880x F 5.7 2.7	800x P 2.3 2.9	1600x VG 9.6 1.7	1140x G 8.1 2.2	1080x P 3.3 2.4
VENUS* 20,000 cd/m²		<2"	5"	500x 1.3	420x 1.4	340x 1.6	700x–1000x 1.2	580x 1.2	440x 1.4	700x–1600x 1.2	700x 1.2	510x 1.2
		1"	2"	500x 1.5	500x 1.6	380x 1.8	1000x 1.2	790x 1.3	560x 1.6	1100x–1600x 1.2	920x 1.2	700x 1.4

12.8. EYE SPECTRAL AND INTENSITY RESPONSE, CONTRAST SENSITIVITY

Spectral response

There are two basic types of retinal photo-receptors: **cones**, responding to bright-light conditions, and **rods**, responding to low-intensity light. Depending on their spectral sensitivity, the former belong to either **L** (long-wavelengths sensitive), **M** (mid-wavelengths sensitive) or **S** (short-wavelengths sensitive) cones. By combining their separate inputs, the brain creates colors. The cones are concentrated in the center of retina (fovea), where they are as small as ~2μ in diameter. That puts the angular size of the smallest individual foveal cones at ~1/3 arc minute. Cones become larger - up to about four times - toward outer areas of the retina.

Therefore, eye spectral response is directly related, and influenced by illuminance levels (light intensity) to which it is exposed. Illuminance level determines the level of activity of cones and rods, and with it main characteristics of human vision (**FIG. 166**).

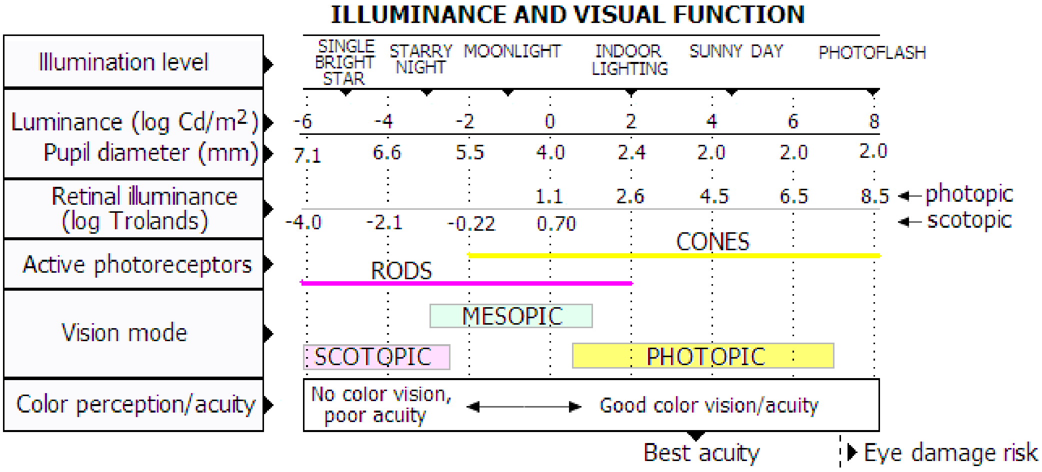

FIGURE 166: The main three modes of eye function under different illuminance levels, **photopic** (bright light), **scotopic** (low light conditions) and **mesopic** (intermediary), result from the specific response of its two types of photoreceptor cells, cones and rods. Their activity is specific to retinal illuminance level, which is determined by the brightness level of the object observed, as well as brightness of the background and surroundings. Unit of retinal illuminance is *Troland*, defined as retinal illumination for $1mm^2$ of pupil area exposed to $1Cd/m^2$ ($Candelas/m^2$) luminance (i.e. one Troland is luminance in $1Cd/m^2$ multiplied with pupil area in mm^2). Due to different modes of operation, size and distribution, cones and rods have different level of retinal illuminance for a given input: photopic (cone) retinal illuminance is proportional to a weighted sum of the photons absorbed by **L**- and **M**-cones, while for the scotopic (rod) illuminance is proportional to the number of photons absorbed by rods (based on Hood and Finkeistein, 1984).

Sensitivity of cones and rods varies with the wavelength, within so called **visible spectrum**, extending from ~370nm to ~730nm. Energy level corresponding to the wavelength of light wave - inversely proportional to the wavelength, and in proportion to the frequency (photon of light has the energy E=hv, **h** being the Plank's constant, and **v** the frequency, a number of waves per unit of time) - stimulates eye photoreceptors, which send received stimulus to the brain. Specific combinations of stimuli from the three different cone receptor types produce an input from which the brain creates perception of color.

VISIBLE SPECTRUM OF LIGHT		
Vacuum wavelength (nm)	Frequency (10^{12}Hz)	Brain color response
730-622	410-482	RED
622-597	482-503	ORANGE
597-577	503-520	YELLOW
577-492	520-610	GREEN
492-455	610-659	BLUE
455-370	659-810	VIOLET

In general, eye sensitivity to light increases exponentially with the decrease in light intensity, with the wavelength of peak sensitivity shifting from ~550nm in day-light conditions, to ~510nm in darkness. As illuminance decreases, cone function transforms toward more effective light collection (elevated pigments level, suppression of lateral inhibition, and convergence of individual outputs) at a price of lower acuity. Bellow certain illumination level, cone function enters dormancy, but cones are still ready to respond to a sufficiently intense light.

On the other hand, decreasing illumination level stimulates accumulation of rhodopsin (pigment) in rods, which was washed out at higher illumination levels. It activates rods, enabling the eye to respond to light stimuli of much lower intensity. As mentioned, this gradual shift in eye sensitivity mode goes through three main stages: (1) photopic, in bright light conditions, (2) mesopic, in low light conditions, and (3) scotopic in near total darkness (**FIG. 167**).

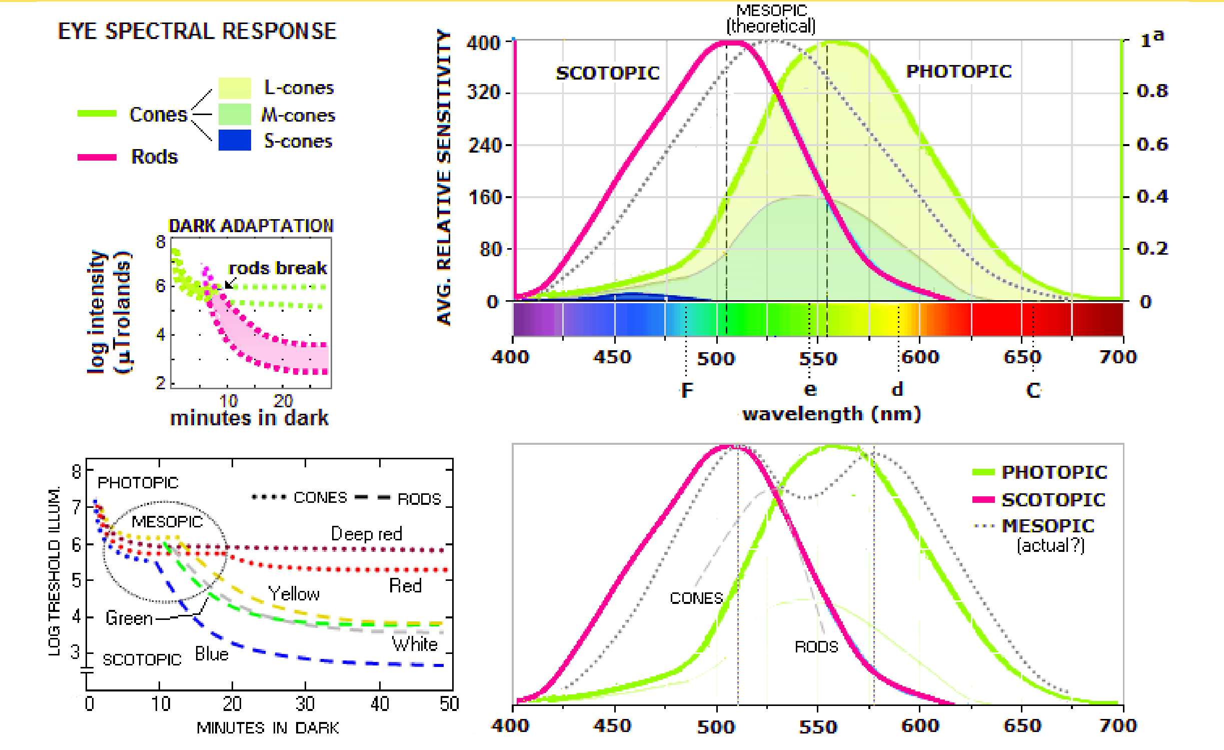

FIGURE 167: **Top right**: Spectral response of the eye. Peak cone sensitivity is over 200 times lower than peak rod sensitivity. Relative sensitivities of **S**, **L** and **M** cones are shown within photopic mode; by combining their inputs, the brain creates colors. **Bottom left**: Exposed to low-light conditions in full photopic mode, cone sensitivity increases 30-100 times within ~10 minutes, reaching its maximum sensitivity level (the darker it is, the faster transition from cones-to-rods function; in near-complete darkness, the cones shut down almost instantly). At the point of cones-rods break, rods become dominant, gaining in sensitivity some 200-1000 times over peak cone sensitivity within the next ~20 minutes (individual sensitivity varies within the shown approximate range: by a factor of ~3 and ~10 for the cones and rods, respectively). In the process, peak sensitivity shifts from ~555nm (photopic) to ~507nm (scotopic). The response range shifts from ~400-730nm to ~370-650nm, respectively. Dark-to-light eye adaptation lasts considerably less: only about 7 minutes.

[a]Maximum sensitivity level, after ~10 min in darkness; maximum bright-light cone sensitivity is 30-100 times lower.

Mesopic eye function is considerably more complex than either photopic or scotopic, due to the simultaneous input of cones and rods, both only partly activated. As a result, there is no agreement (within U.S. or internationally) about its exact modeling. It is most commonly presented as a simple sum of the cones and rods functions, as $V_{mes}=xV_{pho}+(1-x)V_{sco}$, respectively, with **x** varying with illumination level from 0 at the low, to 1 at the high of the mesopic range. As illumination continues to decrease bellow photopic level, this theoretical curve (**FIG. 154** top right) gradually shifts from the photopic to scotopic curve, maintaining a single peak, and similar overall shape.

However, more recent empirical evidence suggests that the actual mesopic sensitivity follows more complex patterns, with a well developed mesopic curve having two main peaks, one converging toward peak rods sensitivity, the other toward yellow range of the spectrum (**FIG. 154** bottom right). Such outcome is logically plausible, since both types of photoreceptors are active, widening eye sensitivity curve. The shift of the cone peak from green to yellow is caused by their relative sensitivity under reduced illumination increasing more in the red and blue than in green/yellow (**FIG. 154** bottom left; keep in mind that the plots to the right show relative sensitivities - cone sensitivity is generally much higher than rods sensitivity). Simply summing up adjusted photopic and scotopic function also neglects the fact that cone sensitivity in mesopic light conditions also increases relative to that in full photopic mode. Similarly to rods, but to a smaller extent, this increase in sensitivity comes at a price of lowered acuity.

Both mesopic plots in **FIG. 154** (right) approximate foveal retinal sensitivity as combined sensitivity of cones and rods. However, actual sensitivity varies from predominantly cone sensitivity in the inner fovea (particularly foveola), to predominantly rods sensitivity toward the outskirts of fovea and further off. In other words, within approximately inner half of the fovea mesopic sensitivity is approximated with the right mesopic wing on the bottom plot, which is higher toward both, red and blue wavelength, than cone sensitivity in the photopic mode. Toward outer portions of foveola, and beyond, where rods become dominant, relative sensitivity increases for medium to short (green-to-violet) wavelengths, and decreases for longer (red) wavelengths, nearly vanishing for the deep red; mesopic sensitivity for this portion of the retina is approximated mainly by the left mesopic wing on the bottom right plot on **FIG. 154**.

Obviously, sensitivity properties of the retina vary greatly with its particular area. Its small off-center portion, foveola, is nearly exclusively covered by a dense cone structure; cones remain dominant up to about half the radius of fovea, an area surrounding foveola, 4-5 times larger in diameter. Outer half of the fovea has a mixed cones/rods structure.

Rods begin to dominate at the outskirts of foveola, nearly exclusively populating the outer area of the retina. They become predominant at less then 1mm away from the retinal center, and peak at about 15° from the it. Similarly to the cones, their size varies from the smallest - about 2.5 microns - in the area of highest concentration, to roughly double that size far out. Rods are more numerous than cones in roughly 100:1 ratio in the retinal area out of the <2mm of central fovea (**FIG. 168**). In the entire retina, rods outnumber the cones approx. 20:1 (120 millions vs. 6 millions). Despite similar average size, rods have much poorer resolution than cones. This is mainly a consequence of so called "convergence": neural output from several rods converge into a single neural brain connection, as opposed to the cones, which have individual neural outputs. Neural convergence of the rods improves sensitivity, sacrificing the resolution.

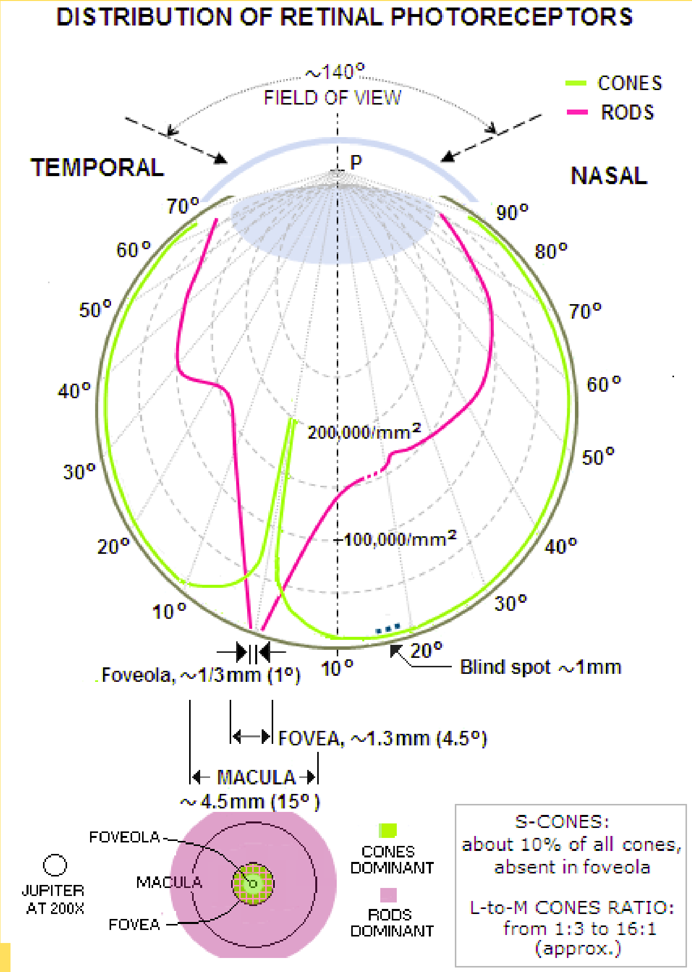

FIGURE 168: Distribution of photoreceptors on the retina of the human eye. The total field of view, approximately 140° is constructed through the principal point (**P**) of the eye. The cones (yellow line), sensitive to bright light, have highest concentration in the small area (foveola) of ~1/3 mm (1°) in diameter, shifted nearly 12° from the optical center. The three cone types, **L** (most sensitive to longer visual wavelengths), **M** (mid wavelengths) and **S** (short wavelengths), have different color pigments, providing input from which the brain creates sensation of colors. The **S** cones are by far the least numerous; also, they are least sensitive, with their main function being supplying the brain with needed input to create color blue. Since the **S** cones are entirely absent from the central ~0.1mm of fovea, this spot is blue blind (it has so called tritanopic vision, in which blue wavelengths are seen as green). The rods (violet line), active in low light conditions, are absent from the central ~1/3 mm of fovea (foveola), but their concentration quickly rises toward the edges of *macula*, and farther out, to reach the maximum some 18° off the foveal center. While rods, similarly to cones, also differ in size depending on their position on the retina (generally being larger in the outer areas), they only have a single pigment, *rhodopsin*. It is ultra-sensitive to light in the green/blue wavelength range but, being a single pigment available in low-light conditions, doesn't allow to the brain to create sensation of color. As the surrounding light intensifies, *rhodopsin* level diminishes, until rods gradually deactivate and cones, also gradually, take over. And vice versa, as the light intensity decreases toward low-light conditions, it falls below the threshold of the cones, while the rods get activated, and become dominant visual receptors. For illustration, size of Jupiter's disc on retina, when magnified 200 times, is shown next to the areas dominated by the cones (smaller than Jupiter's disc), mixed, and rods dominated.

The above comparison of the common size of Jupiter on the retina with the size of its respective cones- and rods-dominated areas suggests that centering an object that requires high resolution in the field of view significantly improves its definition. On the other hand, averted vision will be more helpful with objects where detection is more important than resolution - as long as they radiate mainly in the green-to-violet portion of the visible spectrum. The highest rods acuity is at about 4° from foveola, near to half-radius of the macula. So, for detection of very faint objects, it should work best with the eye directed some 4° off the field center (about 1/5 and 1/10 of the field radius in 40° AFOV and 80° AFOV eyepiece, respectively), with the object centered in the field.

Eye intensity response

Eye response to signal intensity (brightness) is logarithmic for the most part (Weber's law). This means that the perceived signal strength is nearly in proportion to the logarithm of its actual strength (that is, illuminance). For point-like sources, the logarithm base is $100^{0.2}$, upon which was built the familiar concept of stellar magnitude. The response changes for very high level stimuli, due to saturation, and for very low level stimuli, due to the increased role of neural noise (dark light). At very low brightness levels, rod response follows the square root law (de Vries-Rose Law), changing approximately in proportion to the inverse of the square root of mean retinal illuminance.

Eye brightness response, among other factors, also depends on the detail size, length of exposure and background.

Size of retinal image determines how many photo-sensitive retinal cells are stimulated. Telescopic images of extended objects, even with lower surface brightness than that of the object itself, have hundreds of times greater area than the naked eye image, thus stimulating as many more retinal cells. This results in significantly greater *total energy* received by the brain, producing significantly higher perceived brightness. Anyone who has seen the Moon in a telescope can attest to it.

Eye contrast sensitivity

MTF analysis of the image formed by a telescope objective is not a "finished product". To some degree, it will be changed by eyepiece aberrations and, when finally projected onto the retina, it is a subject to the effect of physiological processes. As a result, perceived contrast and resolution limit will depend not only on those inherent to the image, but also on its brightness level and angular size on the retina. The specifics of it are described with the aid of eye *Contrast Sensitivity Function* (CSF), a plot interpolated into empirical data, as shown on **FIG. 169**.

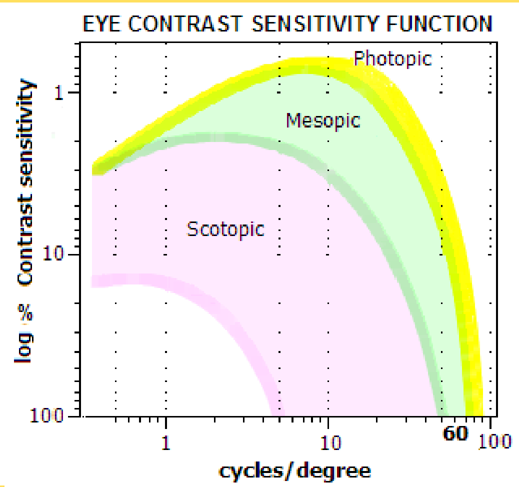

FIGURE 169: Minimum contrast needed by the eye to resolve MTF-like high-contrast pattern, varies with its illumination level and angular size on the retina. Both, spatial frequency (in cycles/degree) and contrast level are given in logarithmic form, to "magnify" the effect at the level of a fraction of the percent in the contrast scale, as well as the effect in the range of large details. Detail size on the retina is given in cycles/degree; 60 cycles per degree is the conventional limit to eye resolution of 1 arc minute. Contrast sensitivity, as a function of detail size and retinal illuminance, is defined by the minimum contrast level at which the image remains resolved. For instance, 10 cycles/degree (6 arc minutes) image size requires 0.6-0.7% minimum contrast in photopic (bright-light) conditions,1-2% in average mesopic conditions, and 10-15% in average scotopic (low light) conditions. Contrast sensitivity peaks for ~9' detail size in photopic conditions, shifting toward larger details in mesopic and scotopic conditions. At the same time, maximum contrast sensitivity diminishes from nearly 0.6% (photopic) to nearly 2% (scotopic). Limiting resolution, at 100% contrast level (along the horizontal scale), also diminishes noticeably with the decrease in illumination being, as expected, the highest in bright-light conditions, and lowest in low-light conditions.

The significance of the CSF for astronomical observing is in helping to determine optimum magnification level for details and objects of different luminosity levels. Like other eye properties, contrast sensitivity can vary widely individually. It is not determined by the quality of the eyesight; an individual with poor eyesight can have better than average contrast sensitivity, and the other way around.

◄ 12.7. Combined eye aberrations, diffraction

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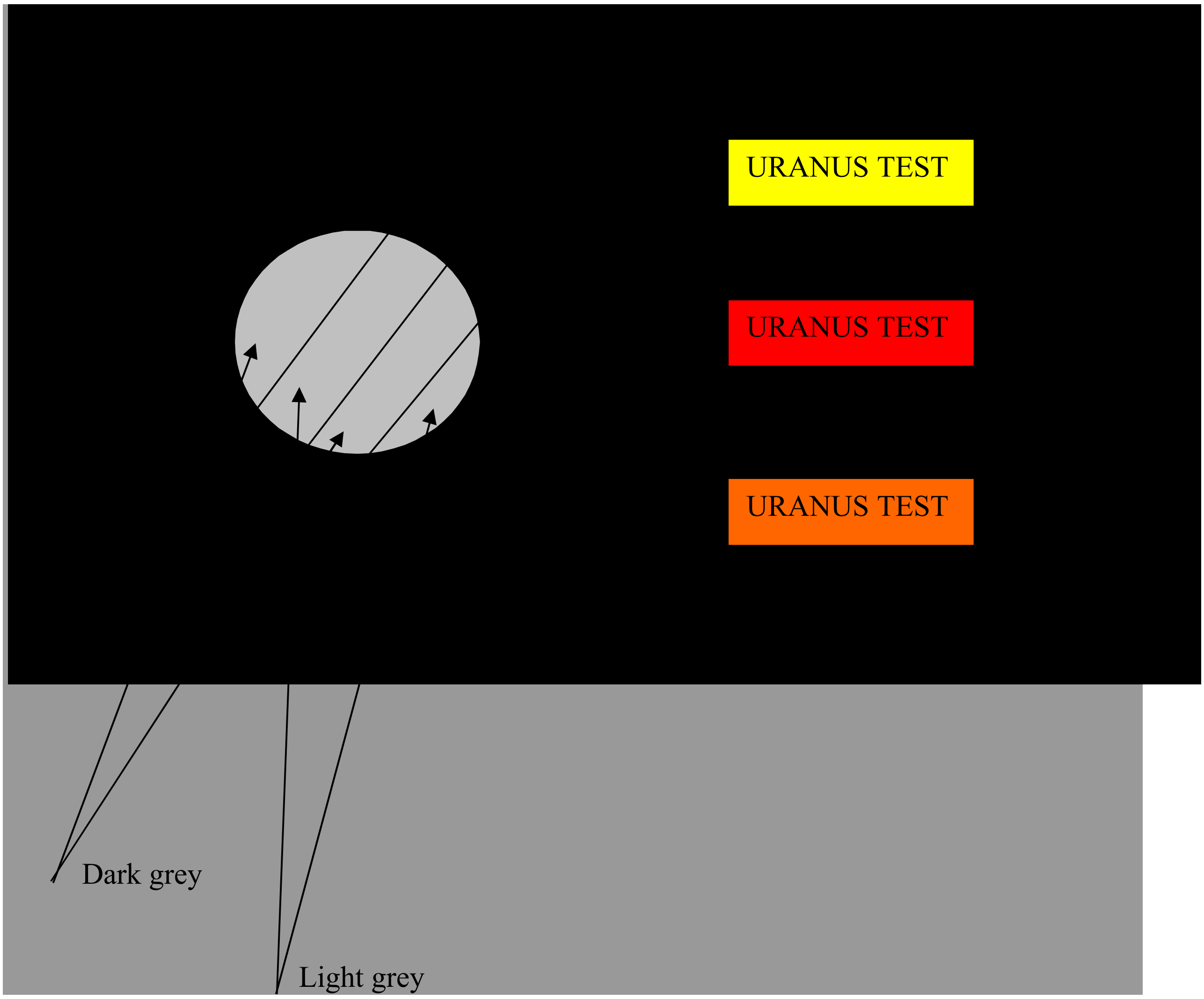
URANUS TEST
URANUS TEST
URANUS TEST
Dark grey
Light grey