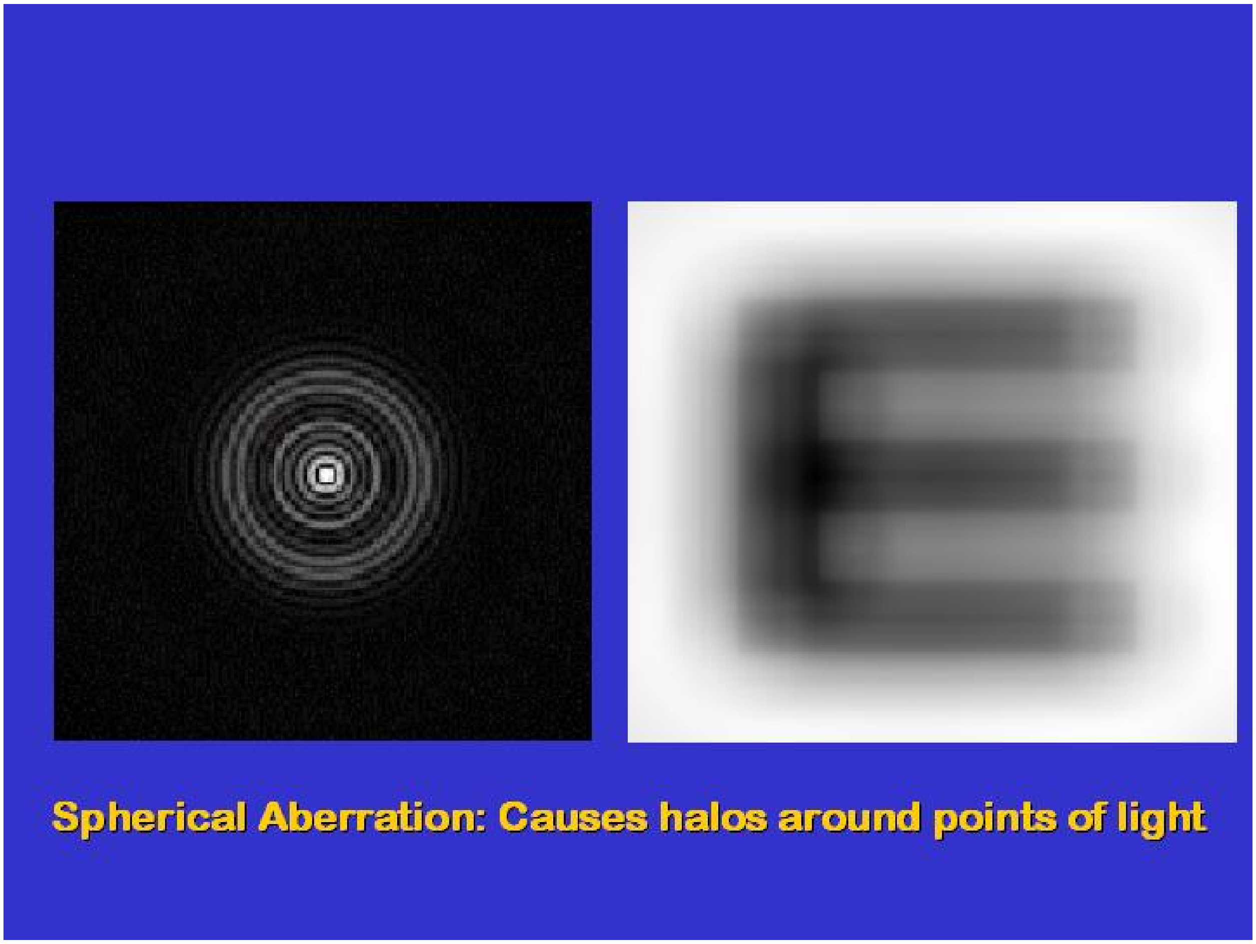
Aberrations in Lens & Mirrors (Hecht 6.3)

- Aberrations are failures to focus to a "point"
- Both mirrors and lens suffer from these
- Some are failures of paraxial assumption

$$\sin(\theta) = \theta - \frac{\theta^3}{3!} + \frac{\theta^5}{5!} \cdots$$

- Paraxial assumption assumes only the first term
- Error results in points having halos around it
- For a image all these add up to make the image fuzzy



Why is Light Focus by a Lens

- Why does all the light focus by a lens
- Consider a curved glass surface with index n' on right side
- Radius of curvature r is centered at C
- Let parallel light ray P at height h from axis hit the curvature at T
- Normal at T is through C forming angle ϕ to parallel beam
- Beam is refracted by Snell's law to angle ϕ' to the normal

$$n \sin(\varphi) = n' \sin(\varphi')$$

Assuming small angles then sin(ϕ)~ϕ and

$$\sin(\varphi) = \frac{n'}{n}\sin(\varphi') \quad or \quad \varphi \cong \frac{n'}{n}\varphi'$$

From geometry for small angles

$$\sin(\phi) = \frac{h}{r} \quad or \quad \phi \cong \frac{h}{r}$$

Angle θ' the beam makes to the axis is by geometry

$$\theta' = \phi' - \phi = \frac{n'}{n}\phi - \phi = \frac{n' - n}{n}\phi \cong \frac{h}{r}\left[\frac{n' - n}{n}\right]$$

Thus the focus point is located at

$$f = \frac{h}{\sin(\theta')} \cong \frac{h}{\theta} \cong h\frac{r}{h}\left[\frac{n}{n' - n}\right] \cong \frac{nr}{n' - n}$$

Thus all light is focused at same point independent of h position

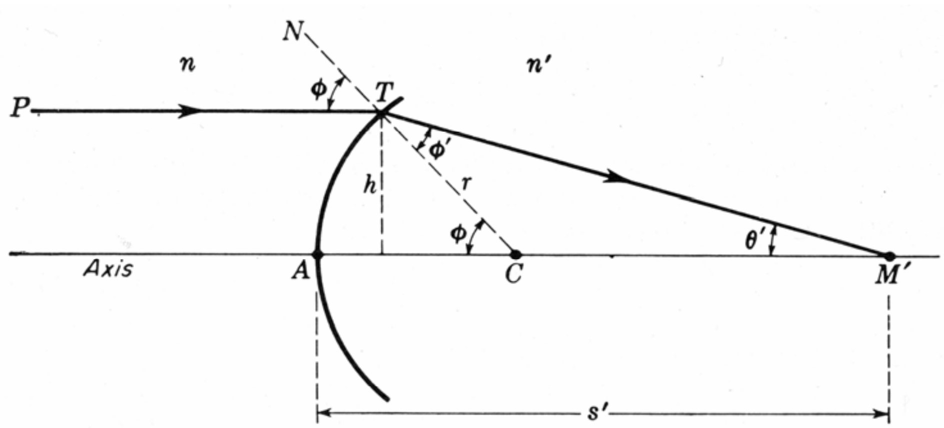


FIGURE 8E
Geometry for ray tracing with parallel incident light.

Spherical Aberrations from Paraxial Assumption

- Formalism developed by Seidel: terms of the sin expansion

$$sin(\theta) = \theta - \frac{\theta^3}{3!} + \frac{\theta^5}{5!} \cdots$$

- Gaussian Lens formula

$$\frac{n}{s} + \frac{n'}{s'} = \frac{n' - n}{r}$$

- Now Consider adding the θ^3 to the lens calculations
- Then the formula becomes

$$\frac{n}{s} + \frac{n'}{s'} = \frac{n' - n}{r} + h^2 \left[\frac{n}{2s} \left(\frac{1}{s} + \frac{1}{r} \right)^2 + \frac{n'}{2s'} \left(\frac{1}{r} - \frac{1}{s'} \right)^2 \right]$$

- Higher order terms add more
- Result now light focus point depend on h (distance from optic axis)

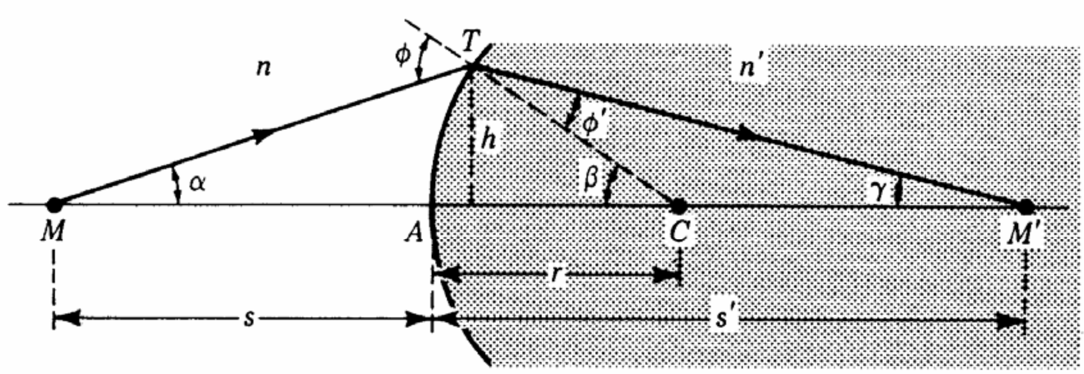
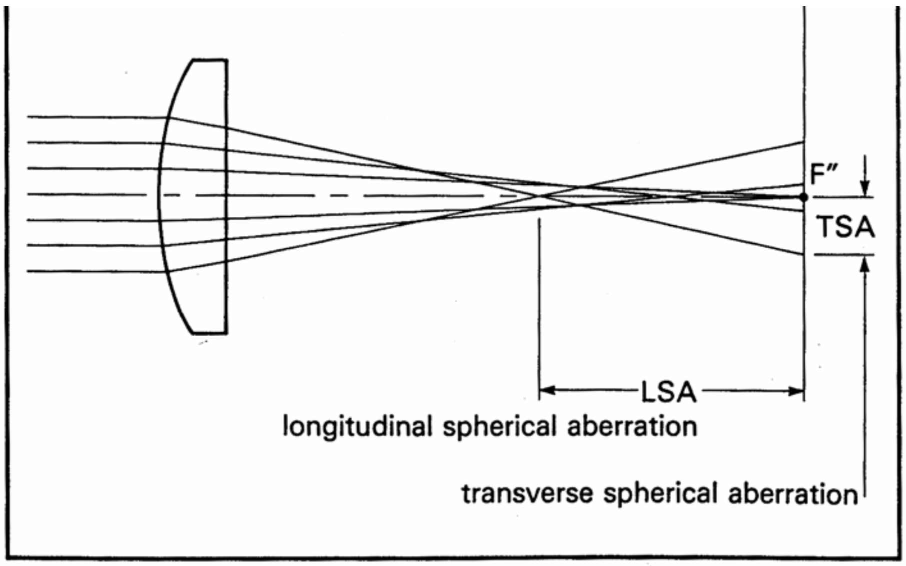


FIGURE 3K
Geometry for the derivation of the paraxial formula used in locating images.

Types of Spherical Aberration

- Longitudinal Spherical Aberration along axis
- Transverse Spherical Aberration across axis
- These create a "circle of least confusion" at focus
- Area over which different parts of image come into focus
- Lenses also have aberrations due to index of refraction issues



SPHERICAL ABERRATION of a plano-convex lens.

Aberrations in Concave Spherical Mirrors

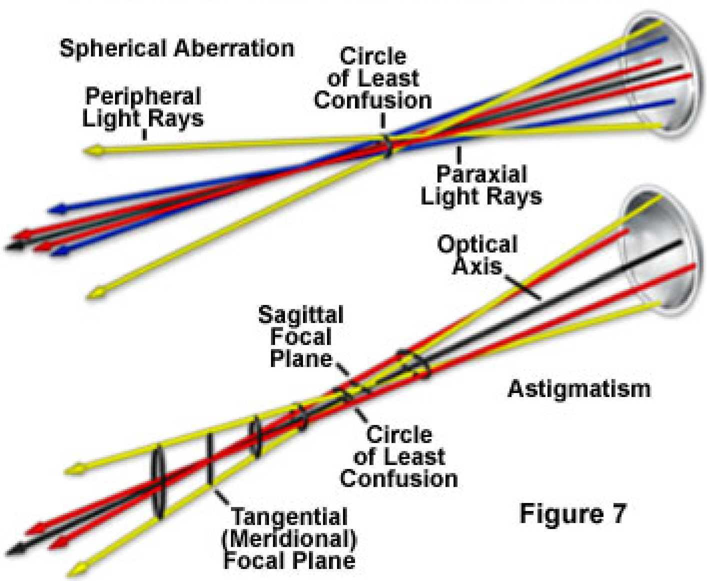


Figure 7

Mirrors and Spherical Aberrations

- For mirrors problem is the shape of the mirror
- Because reflectors generally not wavelength effects
- Corrected by changing the mirror to parabola
- Mirrors usually have short f compared to radius
- Hence almost all mirror systems use parabolic mirrors

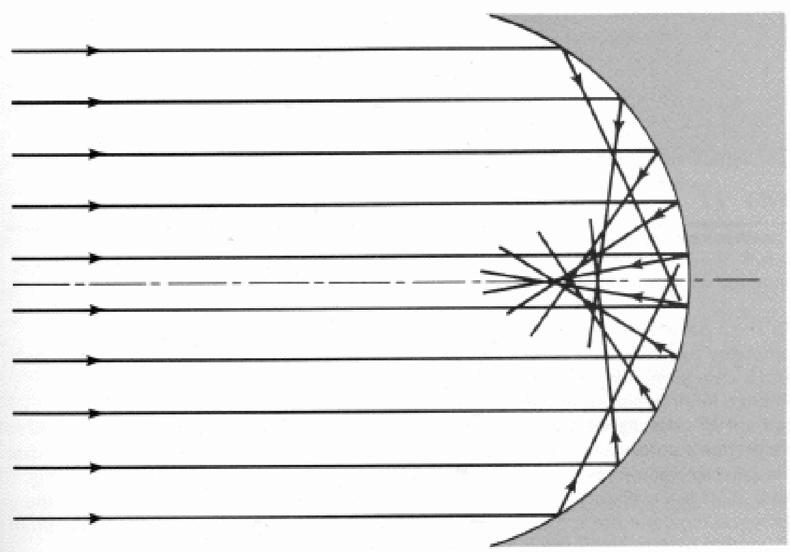
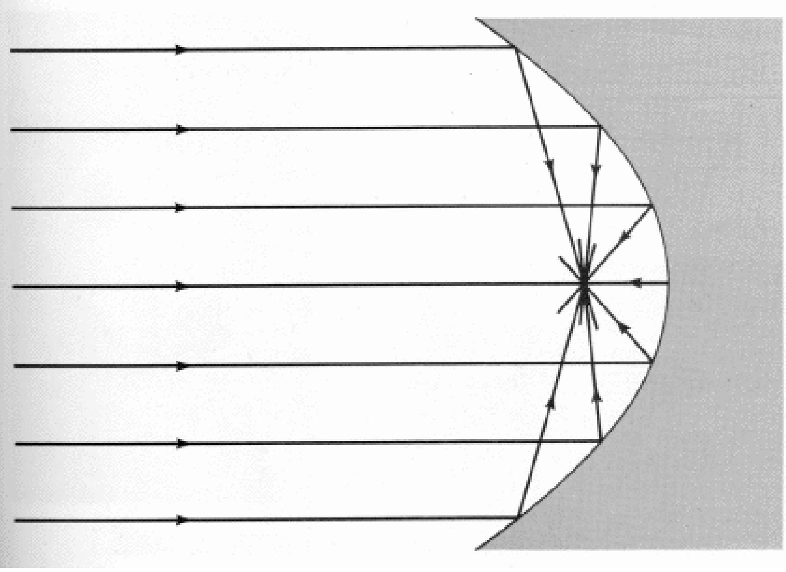


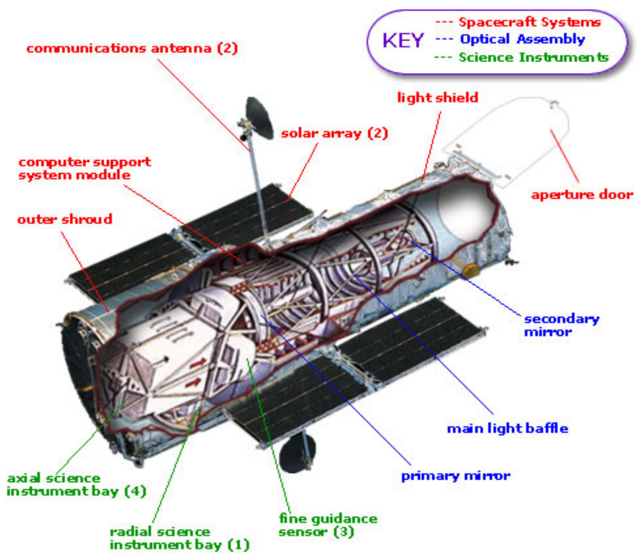
FIGURE 3.35

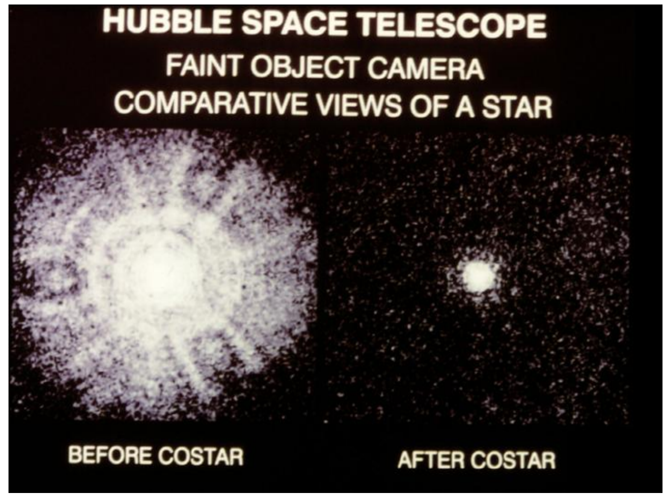
Spherical aberration in a concave mirror.

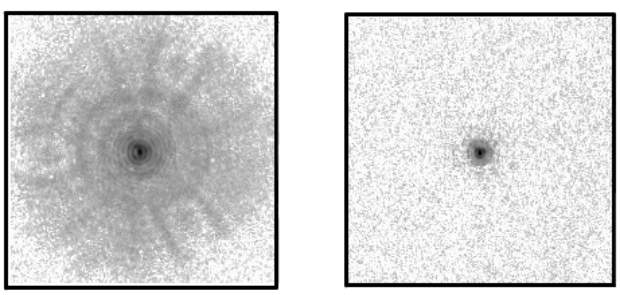


Hubble Telescope Example

- Hubble mirror was not ground to proper parabola – too flat
- Not found until it was in orbit
- Images were terribly out of focus
- But they knew exactly what the errors
- Space walk added a lens (called costar) to correct this



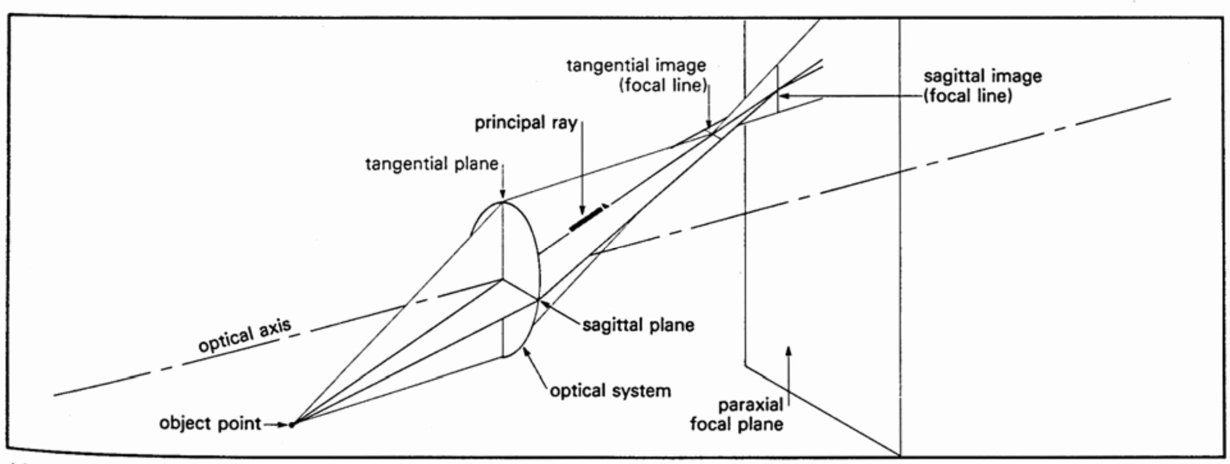




BEFORE COSTAR AFTER COSTAR

Astigmatism Aberration

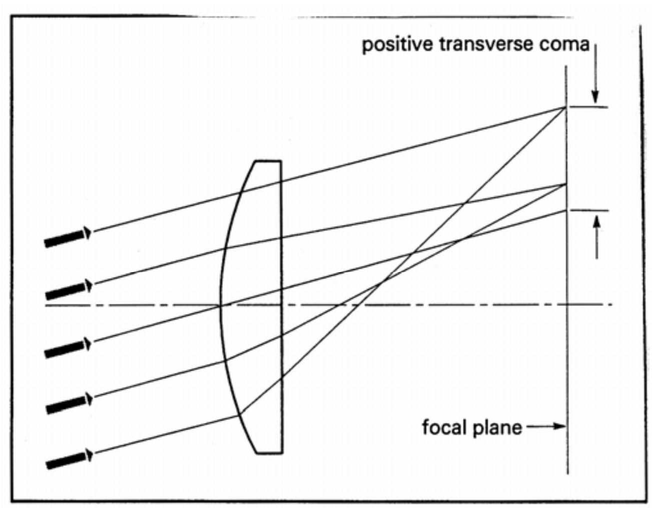
- Off axis rays are not focused at
  the same plane as the on axis rays
- Called "skew rays"
- Principal ray, from object through optical axis
  to focused object
- Tangental rays (horizontal) focused closer
- Sagittal rays (vertical) further away
- Corrected using multiple curves on lens
- Aspheric (not spherical surfaces) shape to give single focus point
- Or can use combine two or more spherical surfaces



ASTIGMATISM can be represented by these sectional views.

Coma Aberration

- Comes from third order sin correction
- Off axis distortion
- Results in different magnifications at different points
- Single point becomes a comet like flare
- Coma increase with NA
- Corrected with multiple surfaces



POSITIVE TRANSVERSE COMA.

Off-Axis Coma Aberration

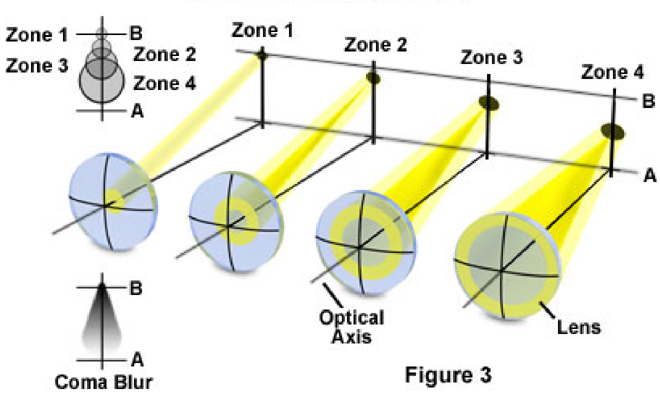
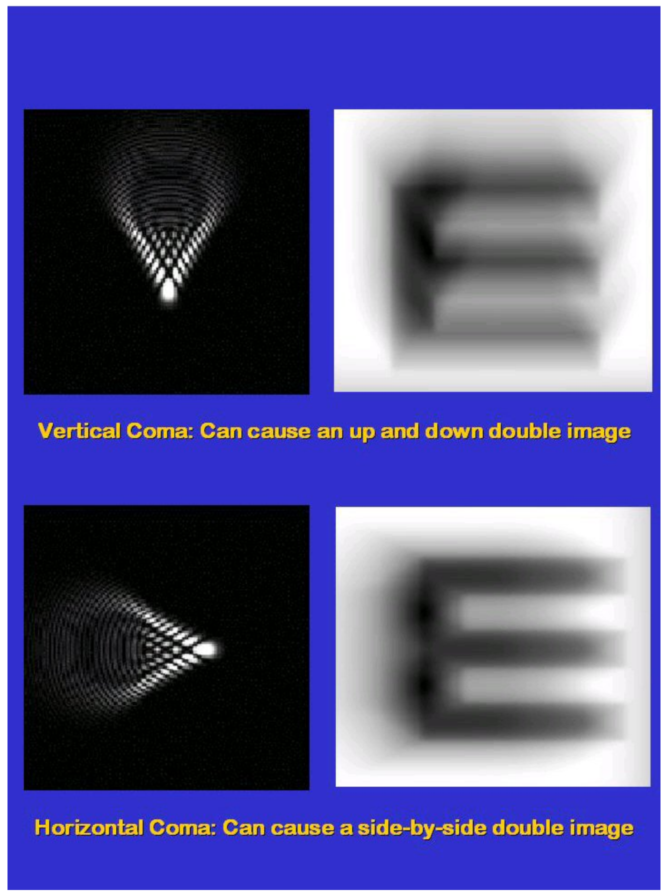
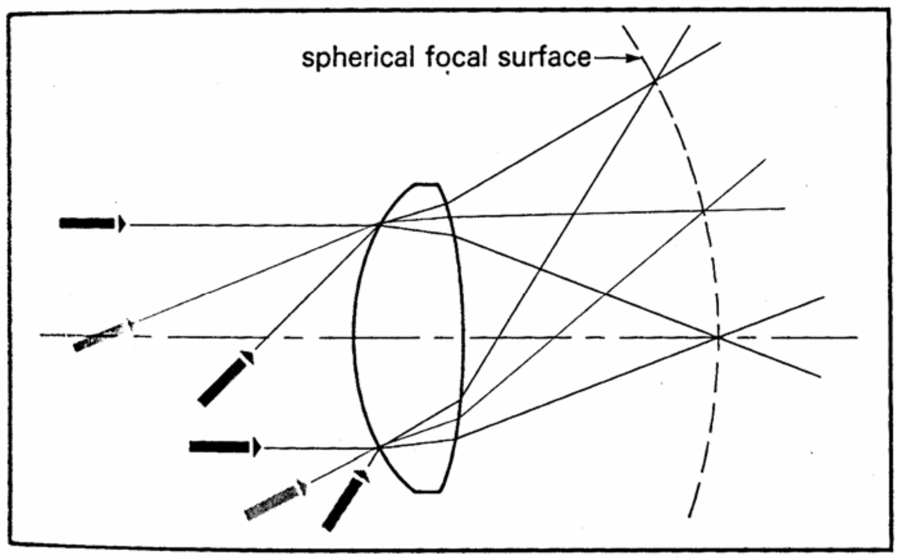


Figure 3



Field Curvature Aberration

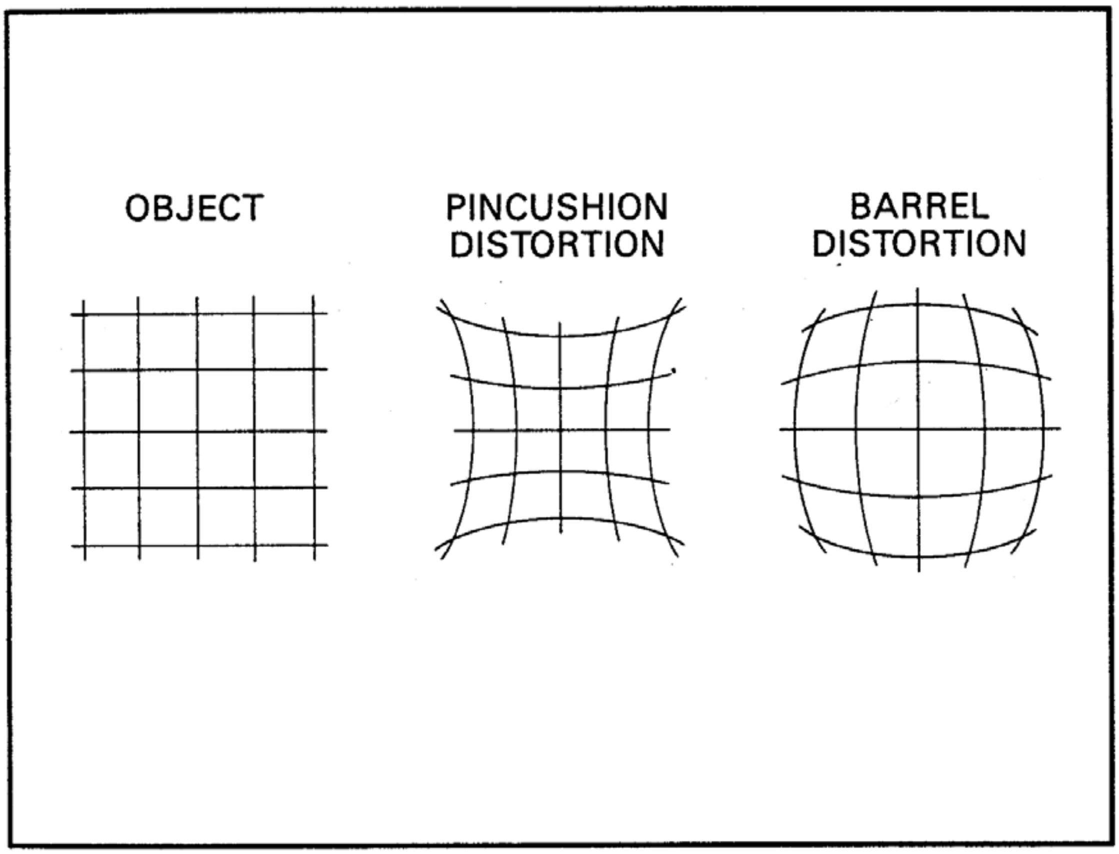
- All lenses focus better on curved surfaces
- Called **Field Curvature**
- positive lens, inward curves
- negative lens, outward (convex) curves
- Reduced by combining positive & neg lenses



FIELD CURVATURE.

Distortion Aberration

- Distortion means image not at paraaxial points
- Grid used as common means of projected image
- **Pincushion**: pulled to corners
- **Barrel:** Pulled to sides



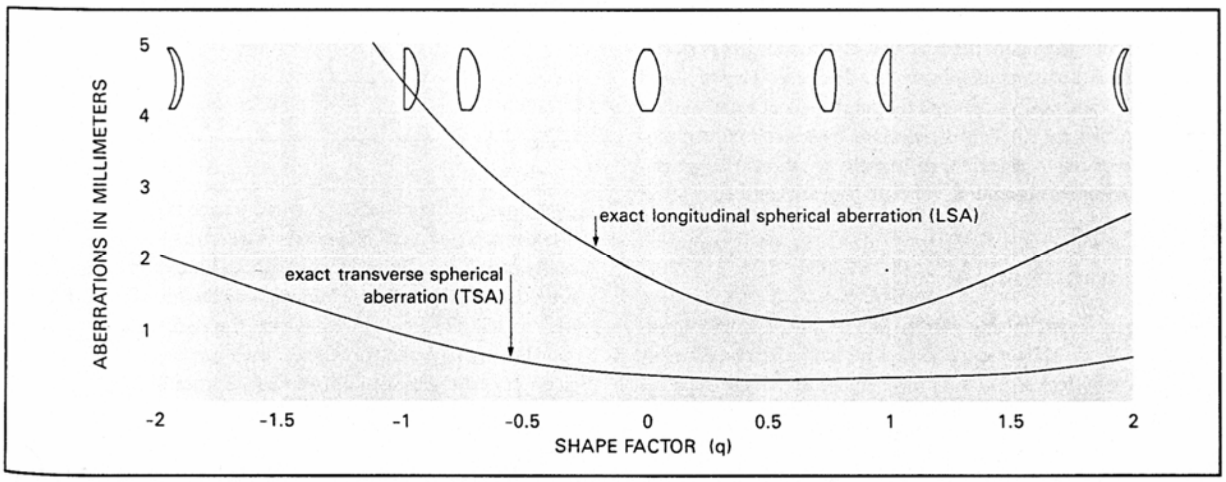
DISTORTION is illustrated by these two image types.

Lens Shape

- Coddingdon Shape Factor

$$q = \frac{r_2 + r_1}{r_2 - r_1}$$

- Shows how aberrations change with shape



ABERRATIONS OF POSITIVE SINGLETS at infinite conjugate ratio as a function of shape.

Index of Refraction & Wavelength: Chromatic Aberration

- Different wavelengths have different index of refraction
- Often list wavelength by spectral colour lines (letters)
- Index change is what makes prism colour spread
- Typical changes 1-2% over visible range
- Generally higher index at shorter wavelengths

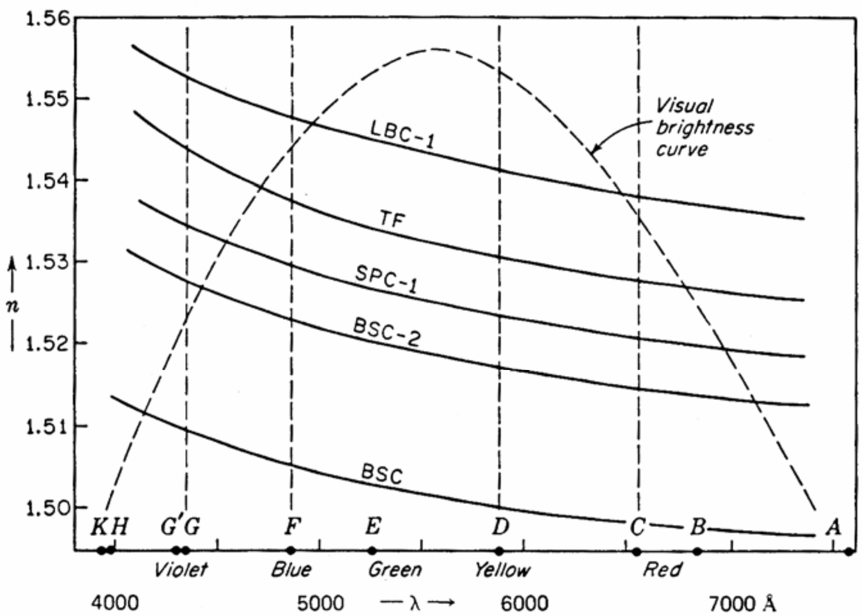


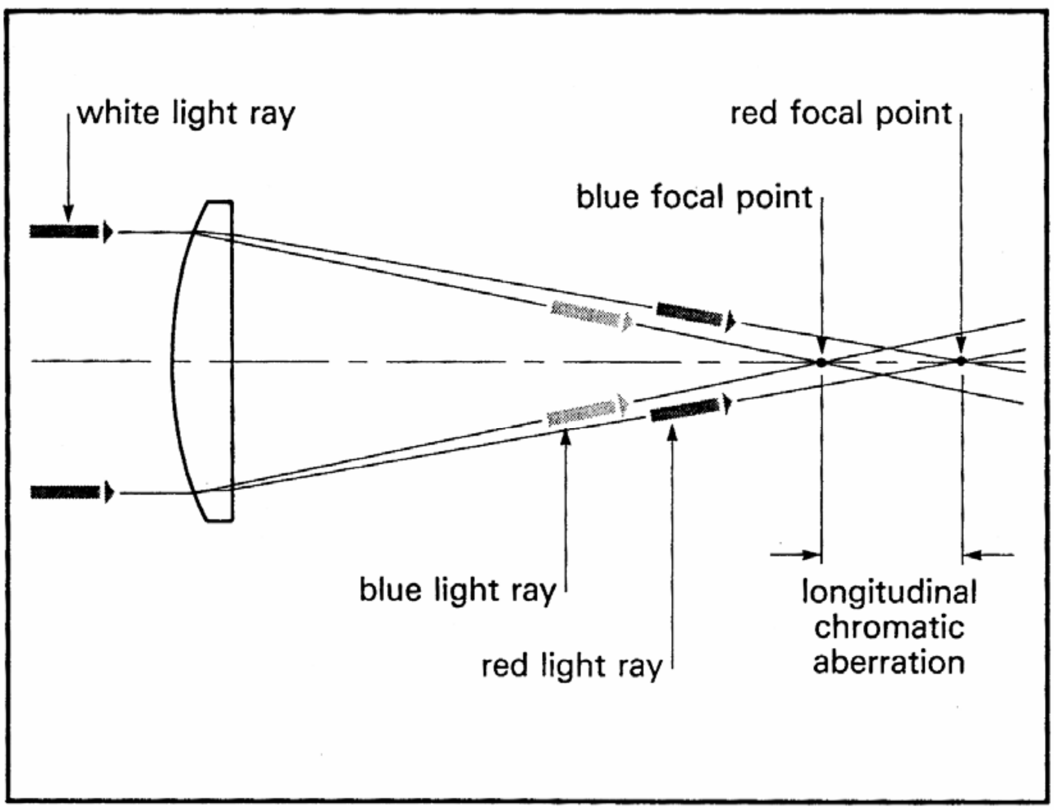
FIGURE 9Y
Graphs of the refractive indices of several kinds of optical glass. These are called dispersion curves.

Table 9E REFRACTIVE INDICES OF TYPICAL OPTICAL MEDIA FOR FOUR COLORS

Medium	Desig- nation	ICT type	ν	n_C	n_D	n_F	n_G
Borosilicate crown	BSC	500/664	66.4	1.49776	1.50000	1.50529	1.50937
Borosilicate crown	BSC-2	517/645	64.5	1.51462	1.51700	1.52264	1.52708
Spectacle crown	SPC-1	523/587	58.7	1.52042	1.52300	1.52933	1.53435
Light barium crown	LBC-1	541/599	59.7	1.53828	1.54100	1.54735	1.55249
Telescope flint	TF	530/516	51.6	1.52762	1.53050	1.53790	1.54379
Dense barium flint	DBF	670/475	47.5	1.66650	1.67050	1.68059	1.68882
Light flint	LF	576/412	41.2	1.57208	1.57600	1.58606	1.59441
Dense flint	DF-2	617/366	36.6	1.61216	1.61700	1.62901	1.63923
Dense flint	DF-4	649/338	33.9	1.64357	1.64900	1.66270	1.67456
Extra dense flint	EDF-3	720/291	29.1	1.71303	1.72000	1.73780	1.75324
Fused quartz	SiO_2		67.9		1.4585		
Crystal quartz (*O* ray)	SiO_2		70.0		1.5443		
Fluorite	CaF_2		95.4		1.4338		

Chromatic Aberration

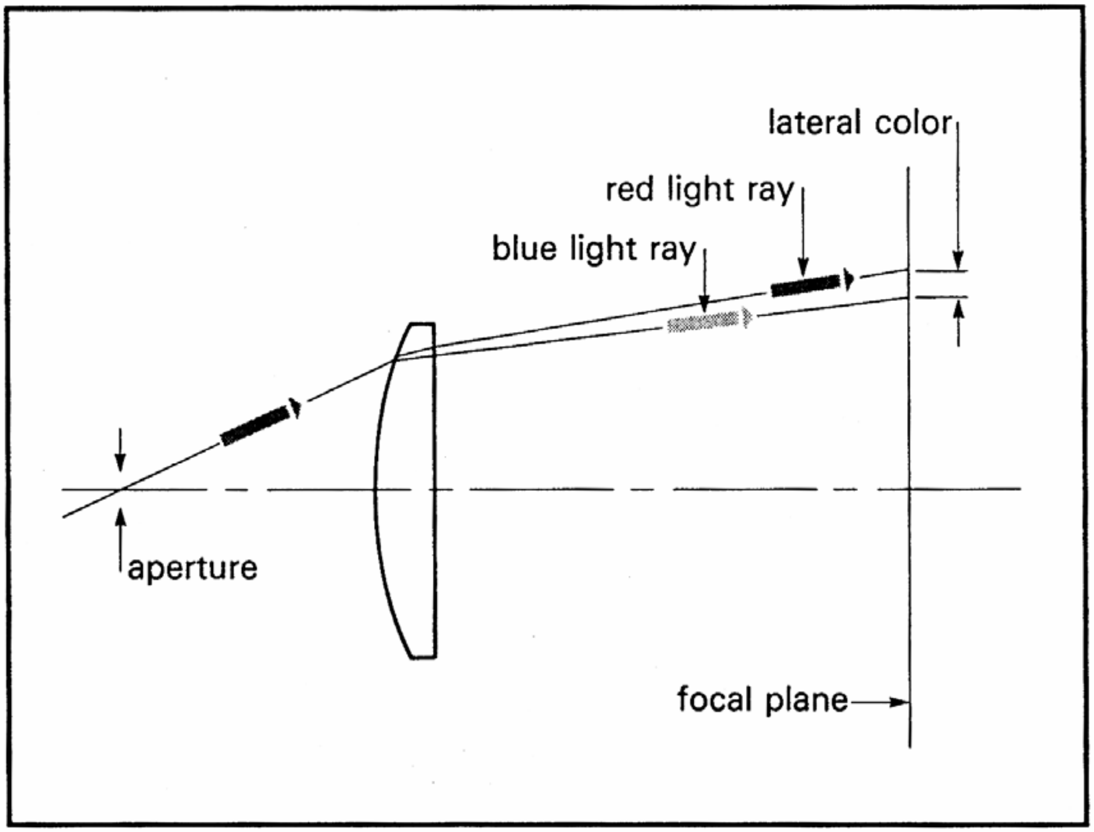
- Chromatic Aberrations
  different wavelength focus to different points
- Due to index of refraction change with wavelength
- Hence focuses rays at different points
- Generally blue closer (higher n)
  Red further away (lower index)
- Important for multiline lasers
- Achromatic lenses: combine different n materials
  whose index changes at different rates
- Compensate each other



LONGITUDINAL CHROMATIC ABERRATION.

Lateral Colour Aberration

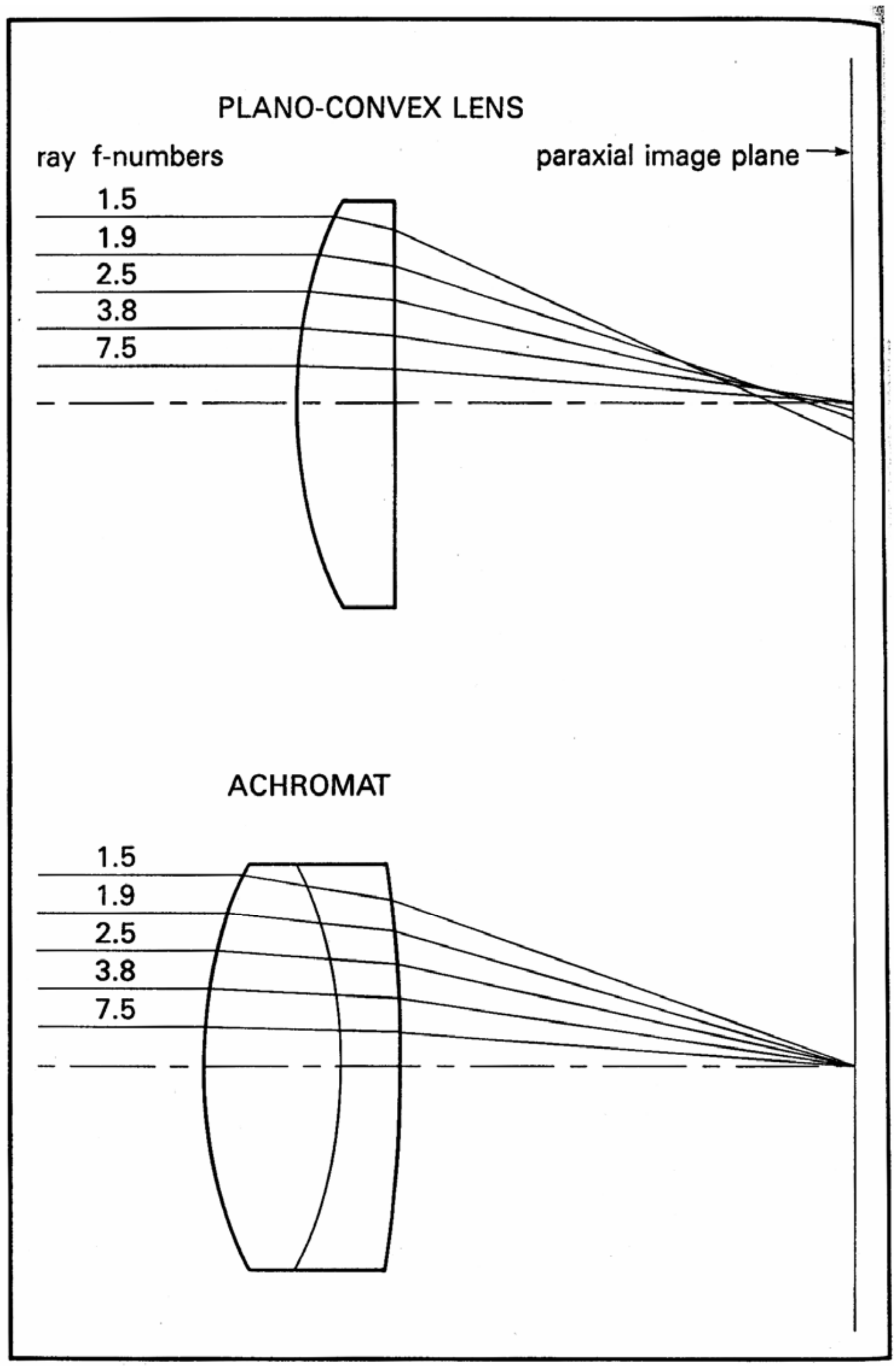
- Blue rays refracted more typically than red
- Blue image focused at different height than red image



LATERAL COLOR is the difference in image height between red and blue rays.

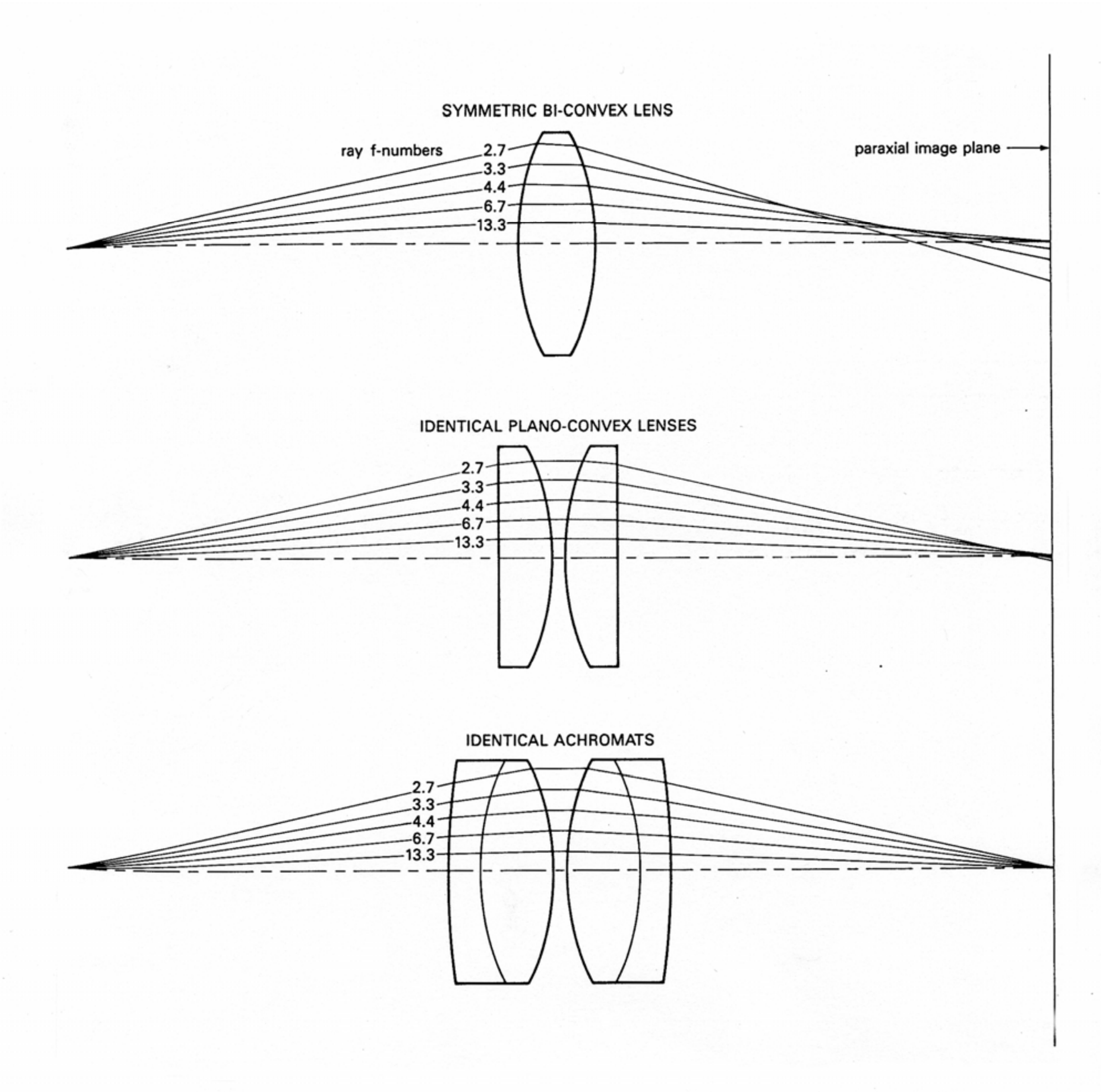
Singlet vs Achromat Lens

- Combining two lens significantly reduces distortion
- Each lens has different glass index
- positive crown glass
- negative meniscus flint
- Give chromatic correction as well



Combined lens: Unit Conjugation

- Biconvex most distortion
- Two planocovex significant improvement
- Two Achromats, best



Materials for Lasers Lenses/Windows

- Standard visible BK 7
- Boro Silicate glass, pyrex
- For UV want quartz, Lithium Fluroide
- For IR different Silicon, Germanium

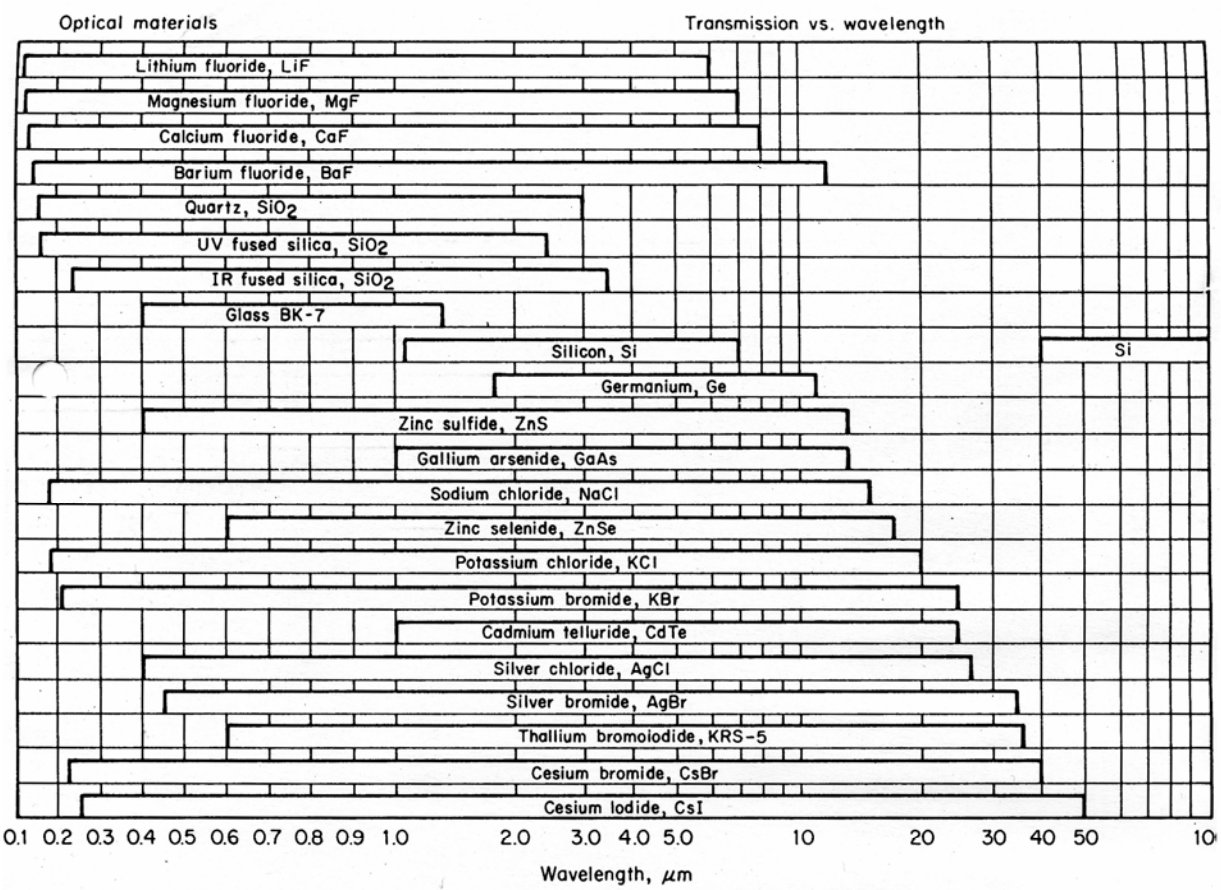


Figure 5.6 Spectral regions at which selected optical materials transmit adequately for optical applications. Note that different forms of silica, including quartz and optical glass, have different transmissions—a consequence of different levels of impurities. *(Courtesy of Jar~s Technology Inc.)*