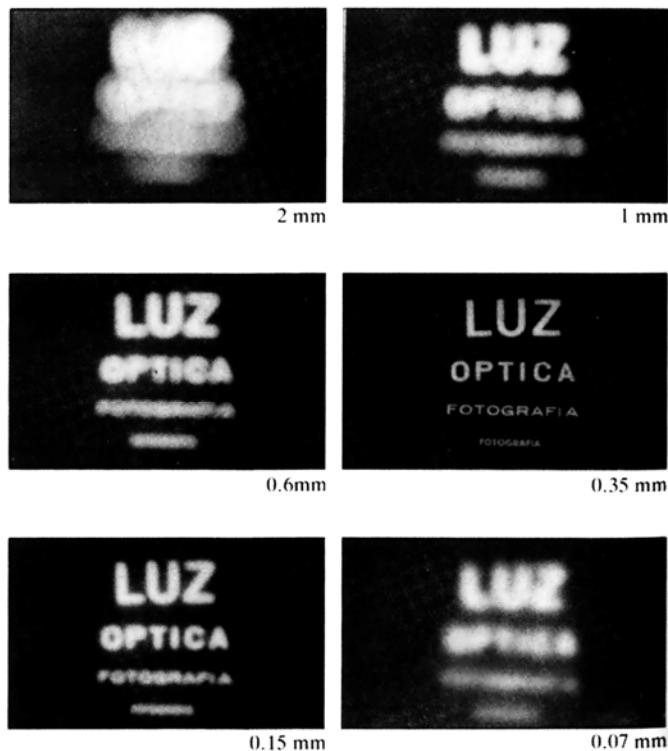
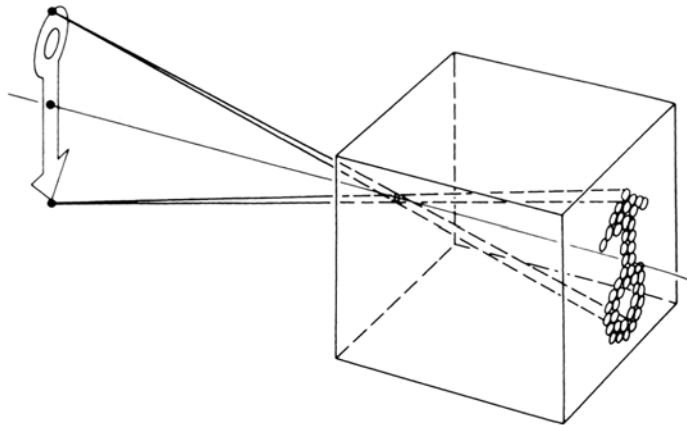


## Optical Systems: Pinhole Camera

- Pinhole camera: simple hole in a box
  - Called Camera Obscura: from Aristotle & Alhazen (~1000 CE)
  - Restricts rays: acts as a single lens: inverts images
  - Best about 0.5-0.35 mm hole at 25 cm distance
  - Advantages: simple, always in focus
- Disadvantages: very low  $f\#$   $\sim 500$ , diffraction limits resolution



**Figure 5.101** The pinhole camera. Note the variation in image clarity as the hole diameter decreases. (Photos courtesy Dr. N. Joel, UNESCO.)

## Classical Compound Microscope

- 2 lens optical systems were the first: microscope & telescope
- Classical system has short  $f_o$  objective lens  
object is near focal length when focused
- Objective creates image at distance  $g$  from focal point
- Objective working distance typically small (20-1 mm)
- Eyepiece is simple magnifier of that image at  $g$
- Magnification of Objective

$$m_o = \frac{g}{f_o}$$

- where  $g$  = Optical tube length
- Eyepiece magnification is

$$m_e = \frac{25}{f_e}$$

- Net Microscope Magnification

$$M = m_o m_e = \frac{g 25}{f_o f_e}$$

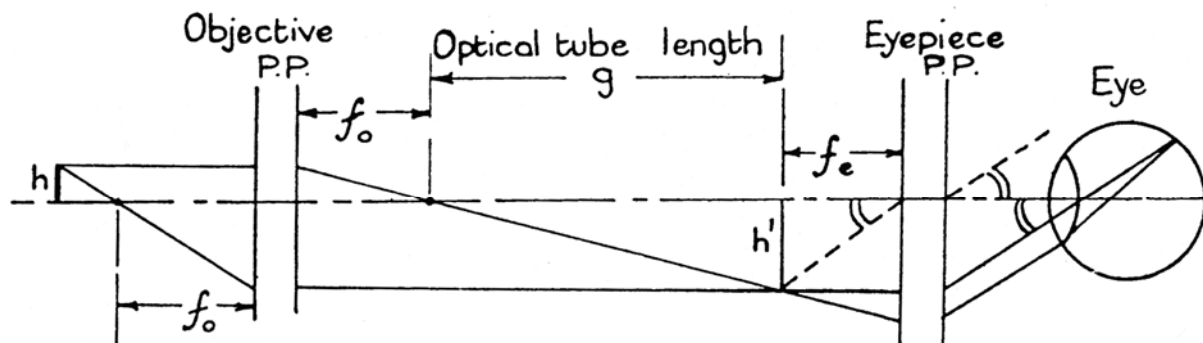
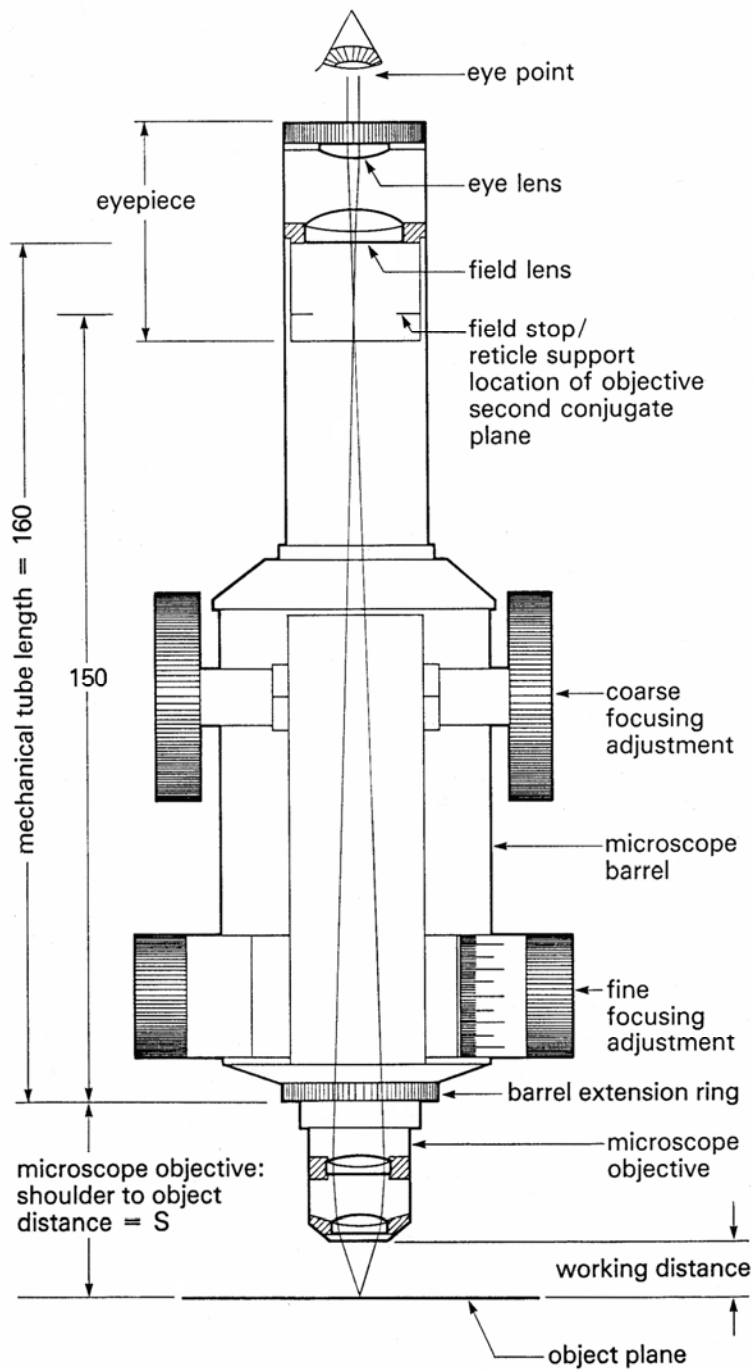


FIG. 96.  
Compound Microscope—Ray Diagram.

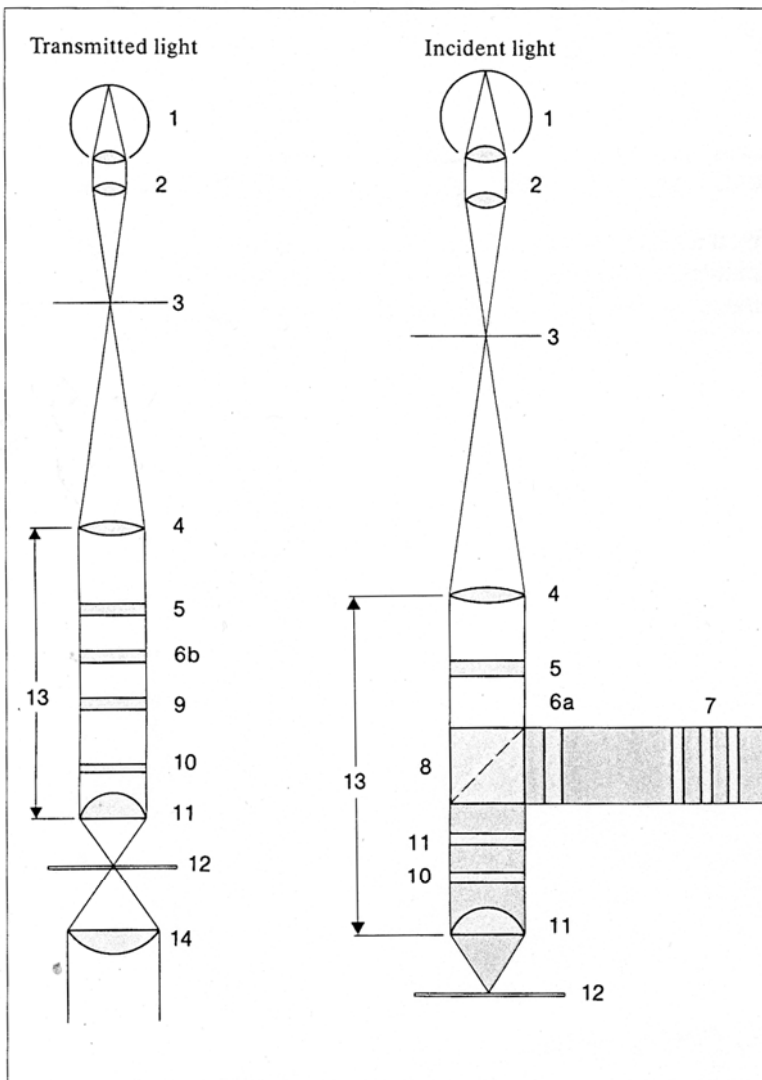
# Classic Microscope

- To change power change objective or eyepiece



## Infinite Corrected Microscopes

- Classical Compound Microscope has limited tube length
- New microscope "Infinite Corrected"
- Objective lens creates parallel image
- Tube lens creates converging image
- Magnification now not dependent on distance to tube lens: thus can make any distance
- Good for putting optics in microscope
- Laser beam focused at microscope focus



### Plan-Apochromat Objectives

These objectives feature Zeiss' highest correction for observation and photomicrography. Their performance is limited only by the laws of physics.

### Ultrafluor Objectives

These special objectives made with quartz lenses are transparent in the UV (down to 280 nm).

- 1 Eye
- 2 Eyepiece
- 3 Intermediate image plane
- 4 Tube lens
- 5 Analyzer slider  
Analyzer slider with  $\lambda$ -plate
- 6a Neutral filter slider AHD  
Polarizer A, fixed HD DIC  
Polarizer for Incident light
- 6b Filter holder  
polarizer D
- 7 3 Filter sliders for selectable  
filters 18 mm dia.
- 8 Reflector slider H  
Reflector slider HD
- 9 Plane for auxiliary specimens  
and compensators for transmitted  
light POL
- 10 DIC slider (in DIC nosepiece)
- 11 Objective
- 12 Specimen plane
- 13 Range of infinite image distance
- 14 Condensor

## Telescope

- Increases magnification by increasing angular size
- Again eyepiece magnifies angle from objective lens
- Simplest "Astronomical Telescope" or Kepler Telescope  
two convex lenses focused at the same point
- Distance between lenses:

$$d = f_o + f_e$$

- Magnification is again

$$m = \frac{\theta_e}{\theta_o} = \frac{f_o}{f_e}$$

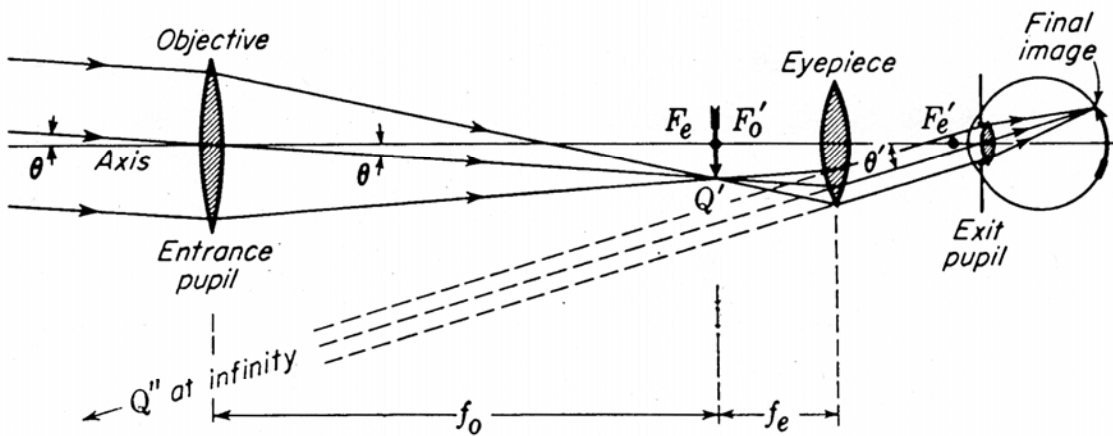


FIGURE 10P

Principles of the astronomical telescope, shown with the eyepiece adjusted to produce the image at infinity.



## Different Types of Refracting Telescopes

- Refracting earliest telescopes – comes from lens
- Keplerean Telescope: 2 positive lenses
- Problem: inverts the image
- Galilean: concave lens at focus of convex

$$d = f_o + f_e$$

- Eyepiece now negative  $f_e$
- Advantage: non-inverting images but harder to make
- Erecting: Kepler with lens to create inversion

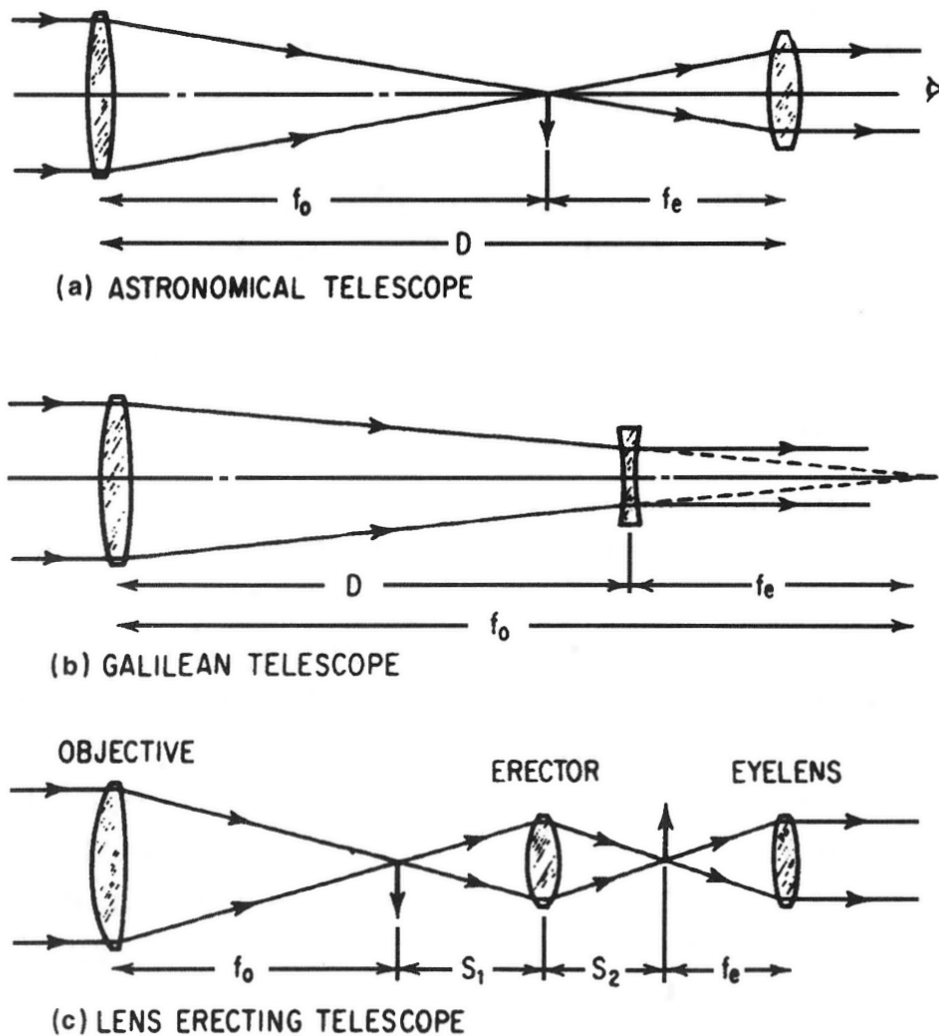
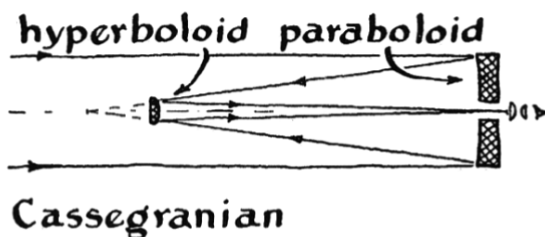
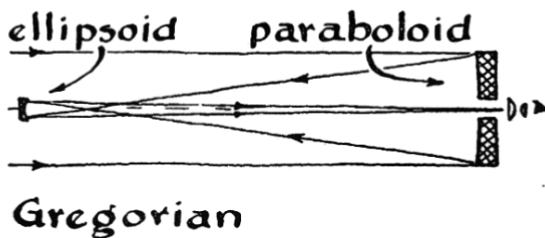
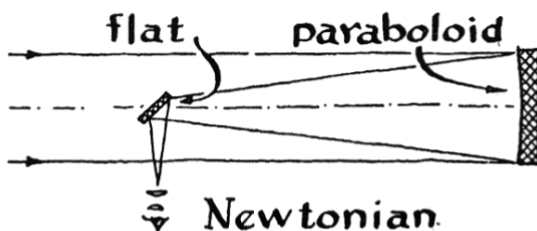
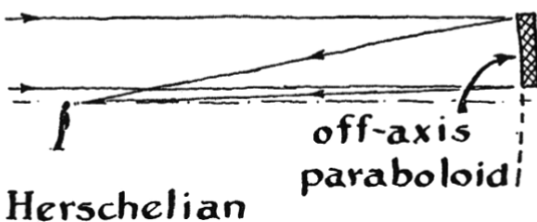
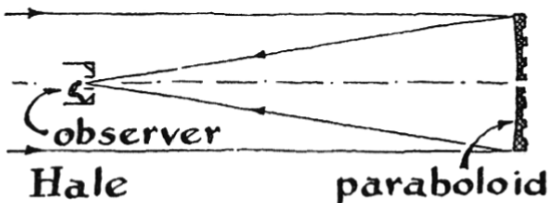


Figure 9.1 The three basic types of telescope.

## Reflecting Telescopes

- Much easier to make big mirrors than lenses
- Invented by James Gregory (Scotland) in 1661
- Hale (on axis observer) & Herschel (off axis) first
- Newtonian: flat secondary mirror reflects to side: first practical
- Gregorian adds concave ellipsoid reflector through back
- Cassegrainian uses hyperboloid convex through back
- Newtonian & Cassagranian most common



## Telescopes as Beam Expanders

- With lasers telescopes used as beam expanders
- Parallel light in, parallel light out
- Ratio of incoming beam width  $W_1$  to output beam  $W_2$

$$W_2 = \frac{f_2}{f_1} W_1$$

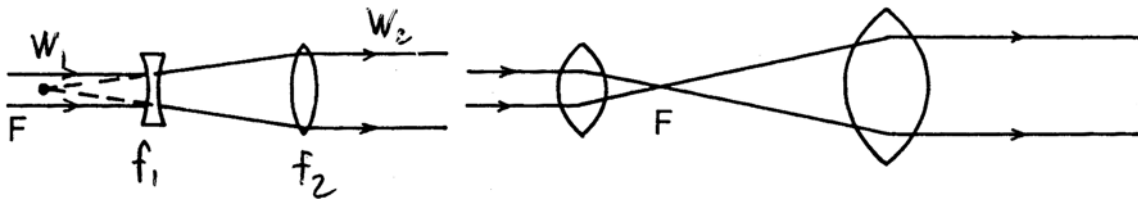


Fig. 4.2.10. Transmissive beam expanders.

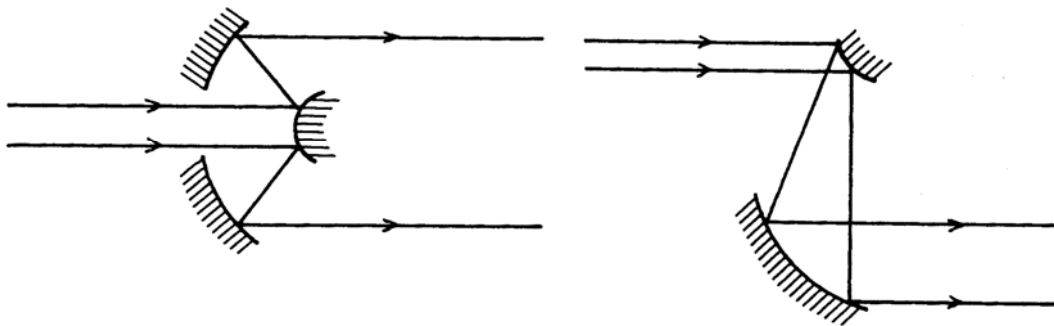
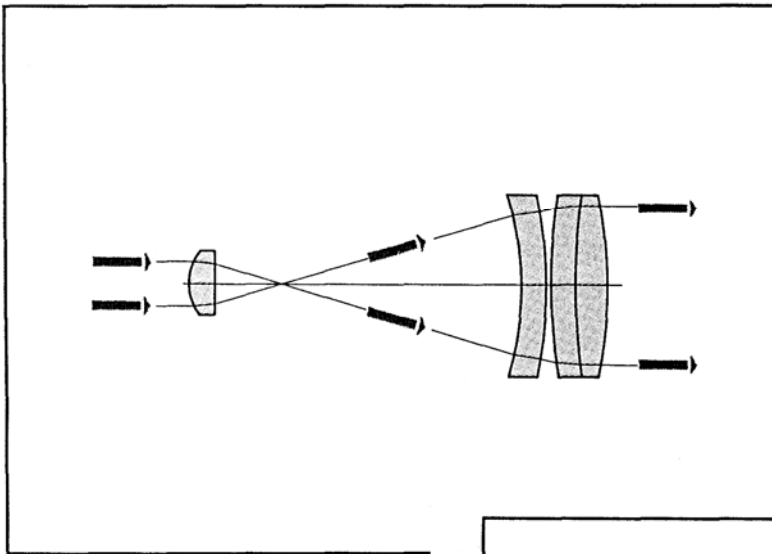


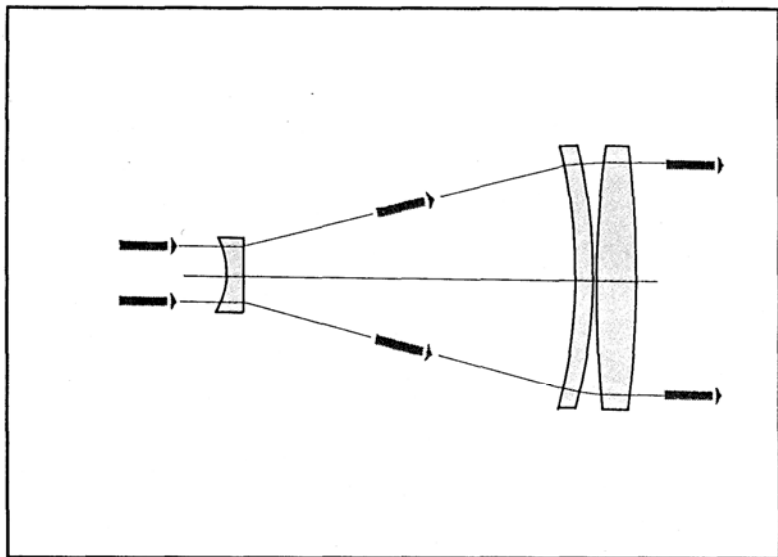
Fig. 4.2.11. Reflective beam expanders.

## Telescopes as Beam Expanders

- Can be used either to expand or shrink beam
- **Kepler** type focuses beam within telescope:
- Advantages: can filter beam
- Disadvantages: high power point in system
- **Galilean**: no focus of beam in lens
- Advantages: no high power focused beam  
more compact  
less corrections in lenses
- Disadvantages: Diverging lens setup harder to arrange



KEPLERIAN BEAM EXPANDER



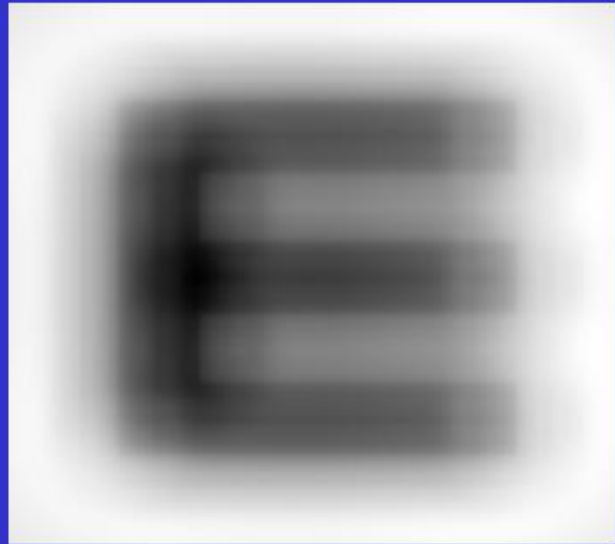
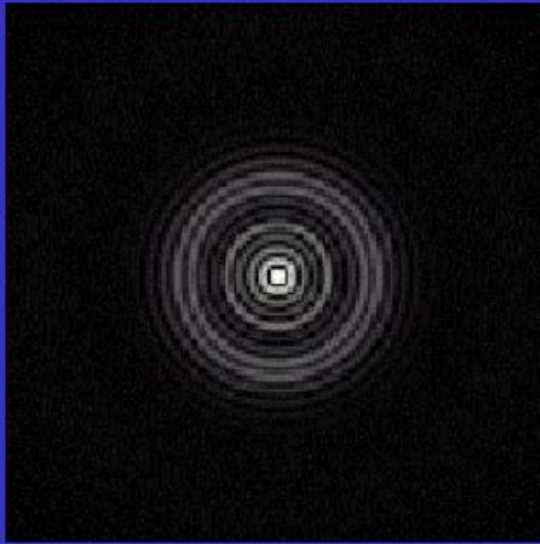
GALILEAN BEAM EXPANDER.

## 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

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

- 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



**Spherical Aberration: Causes halos around points of light**

## Spherical Aberrations from Paraxial Assumption

- Formalism developed by Seidel: terms of the sin expansion

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

- Gaussian Lens formula

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

- Now Consider adding the  $\theta^3$  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)

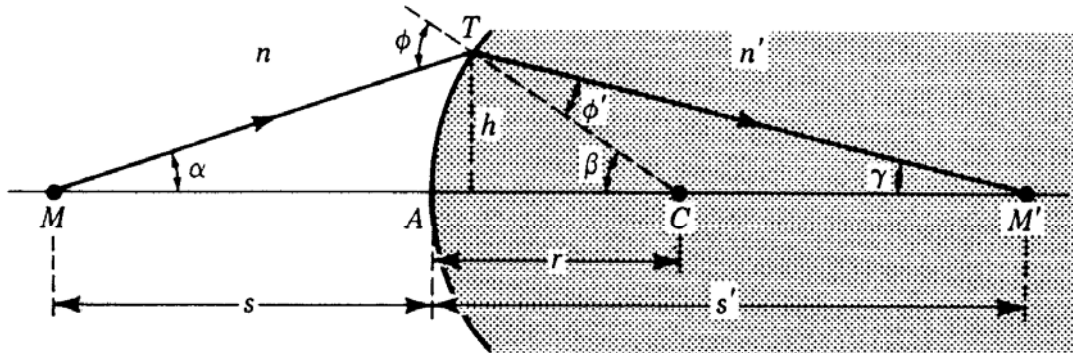
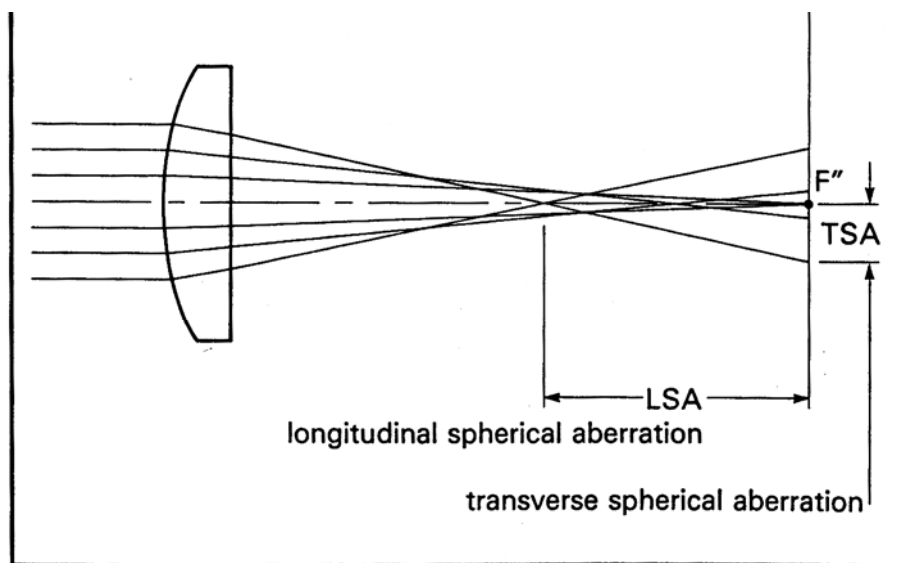


FIGURE 3K

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

## Types of Spherical Aberration

- Formalism developed by Seidel: terms of the sin expansion
- First aberrations from not adding the  $\theta^3$  to the lens calculations
- 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

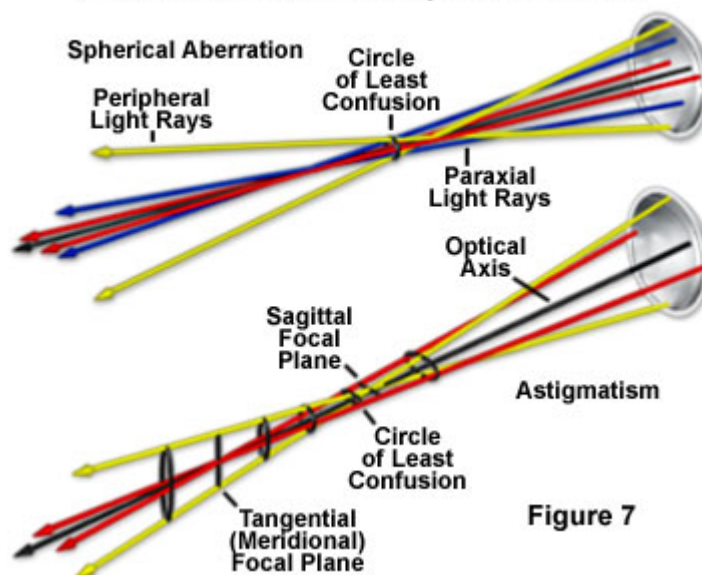


Figure 7

## 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

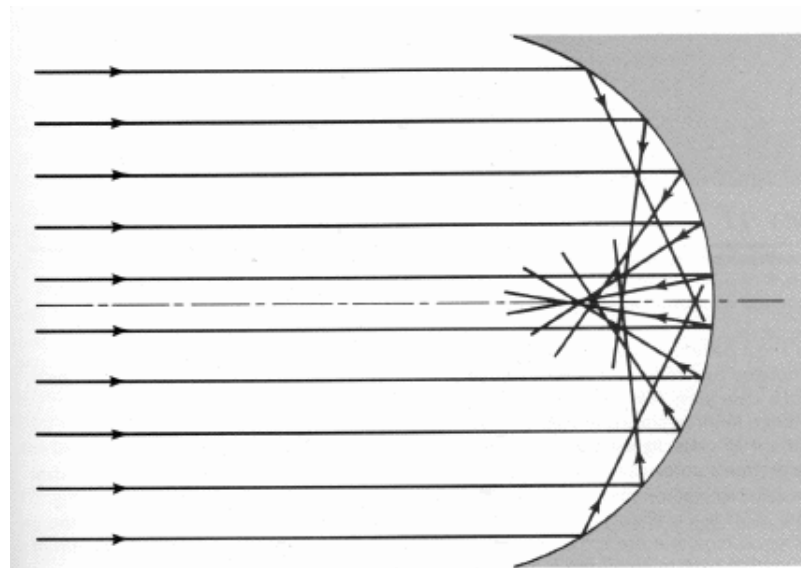
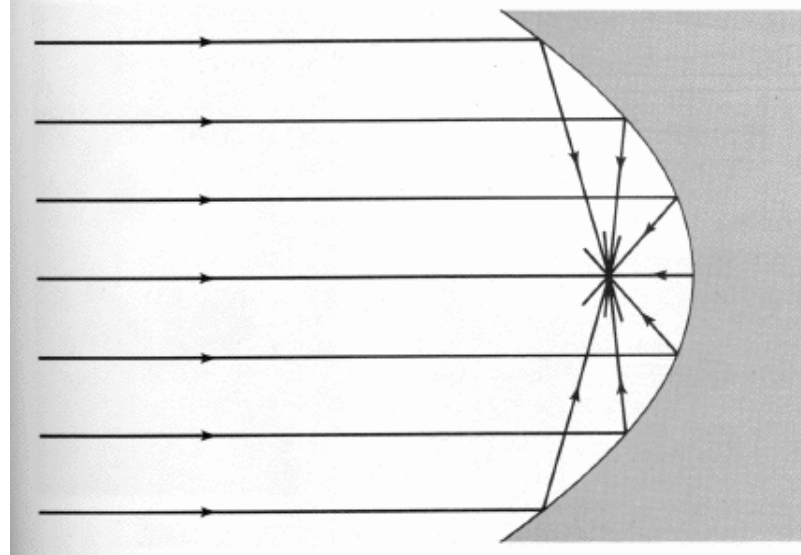


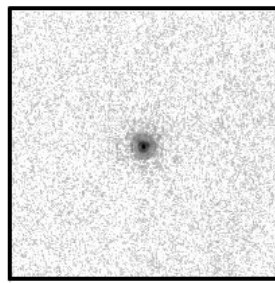
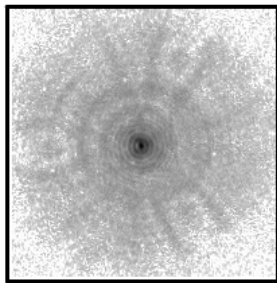
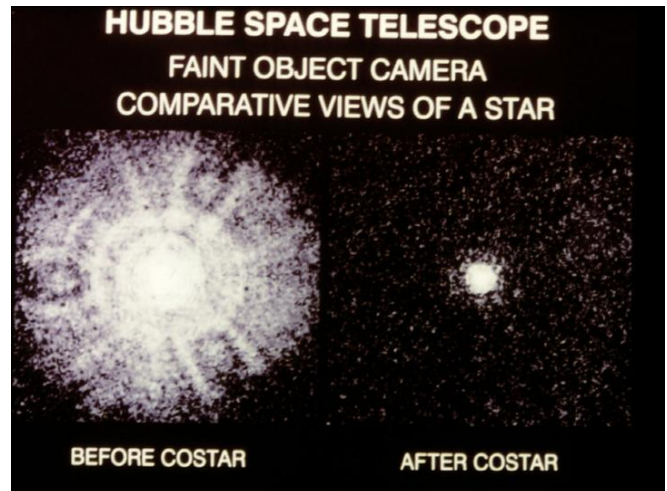
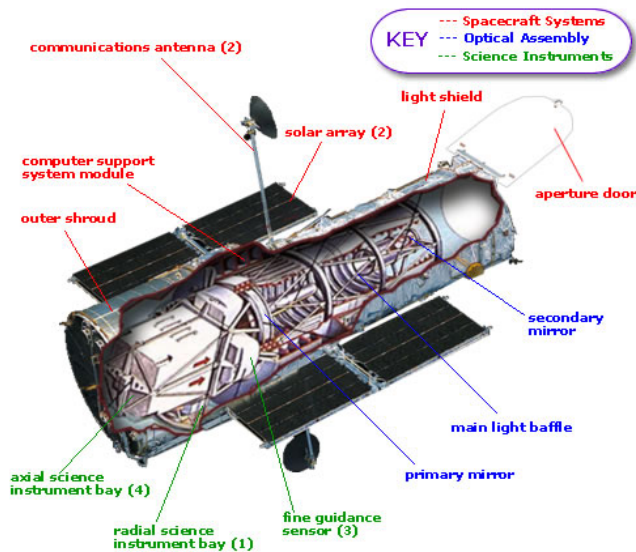
FIGURE 3.35

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



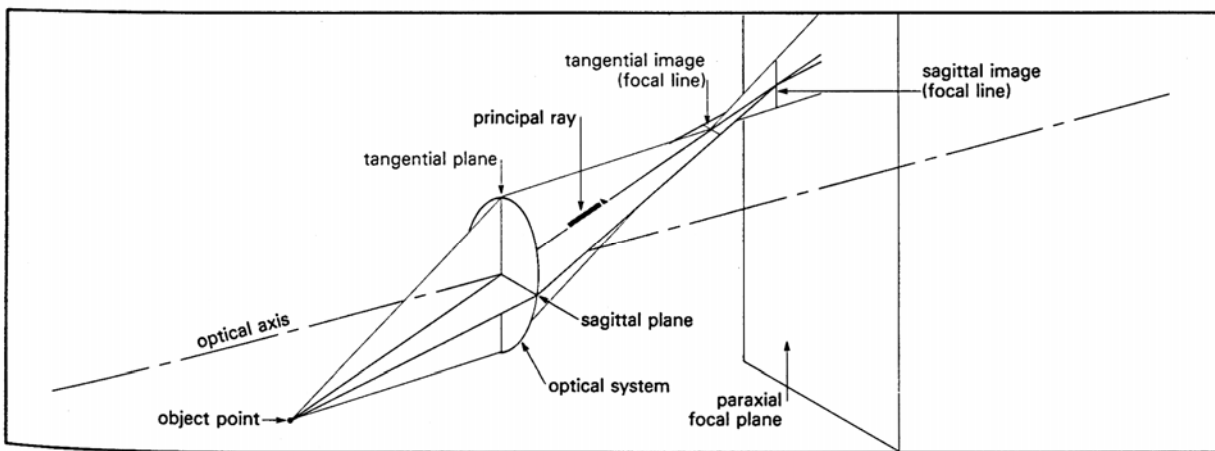
BEFORE COSTAR

AFTER COSTAR

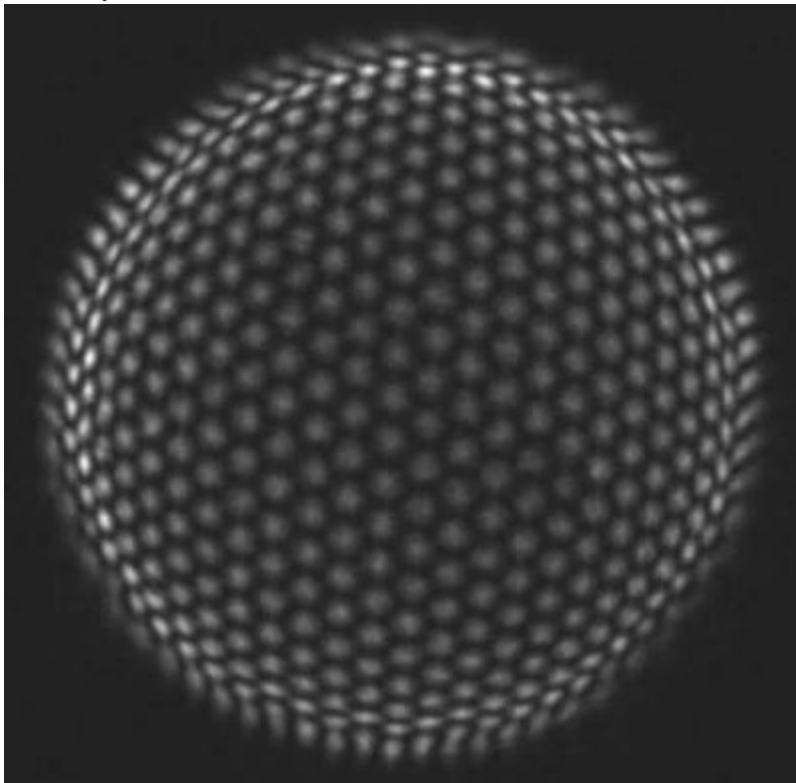


## Spherical Aberration

- 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
- Tangential rays (horizontal) focused closer
- Sagittal rays (vertical) further away
- Corrected using multiple surfaces

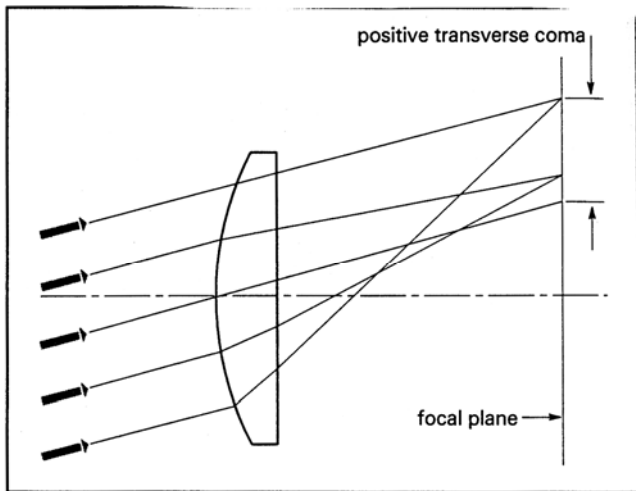


ASTIGMATISM can be represented by these sectional views.



## 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

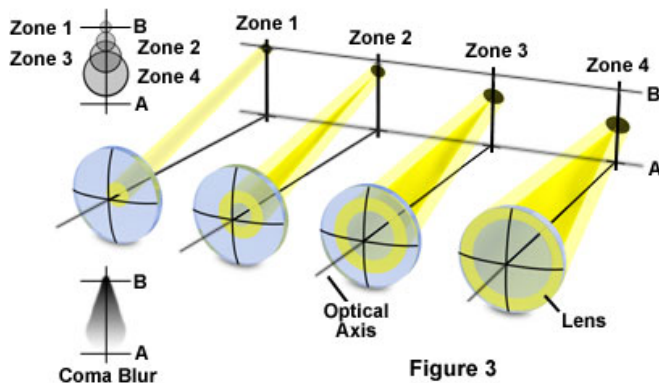
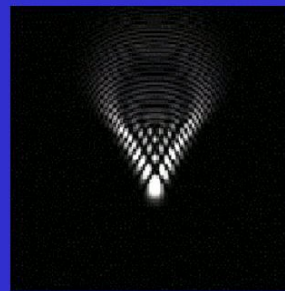
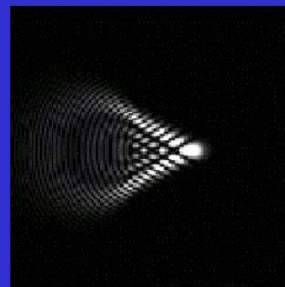
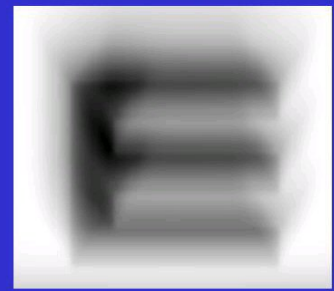


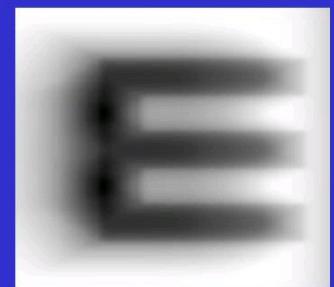
Figure 3



Vertical Coma: Can cause an up and down double image

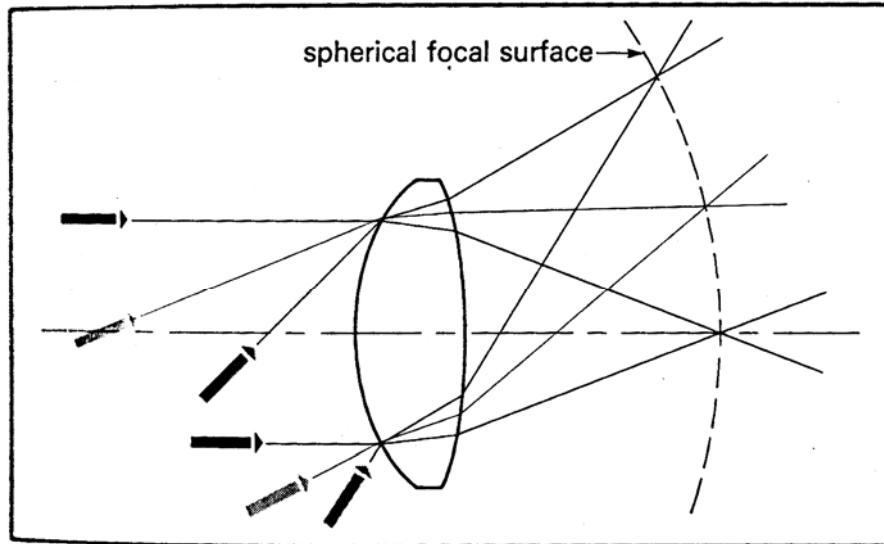


Horizontal Coma: Can cause a side-by-side double image



## 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

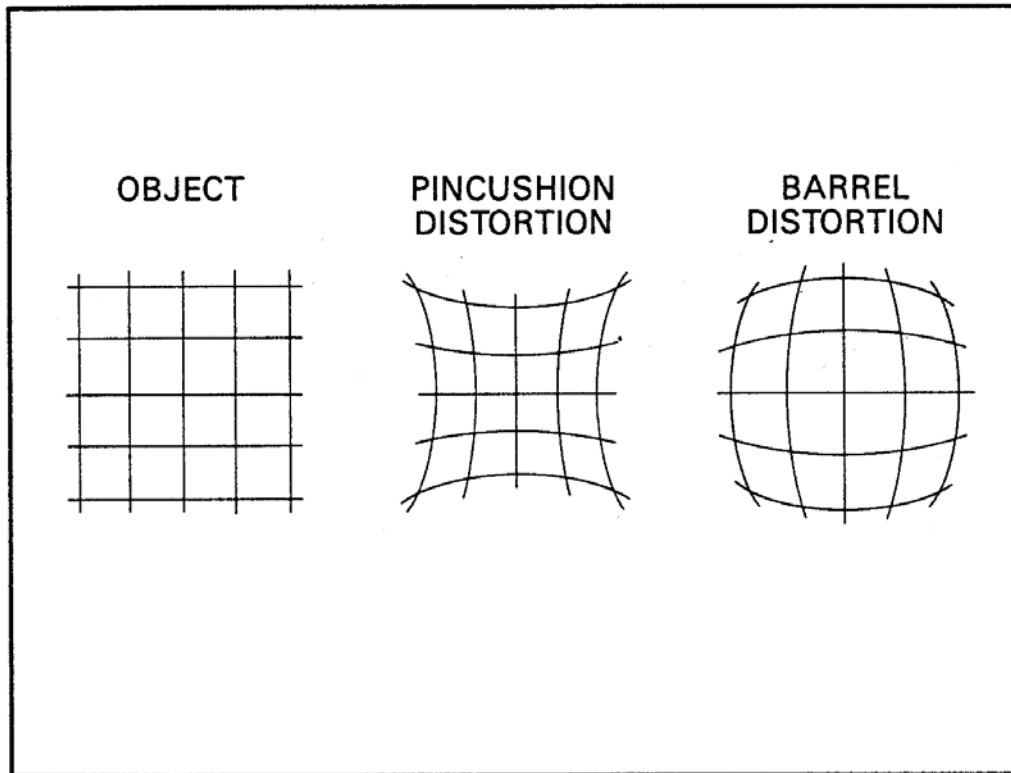


**FIELD CURVATURE.**



## Distortion Aberration

- Distortion means image not at par-axial 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.

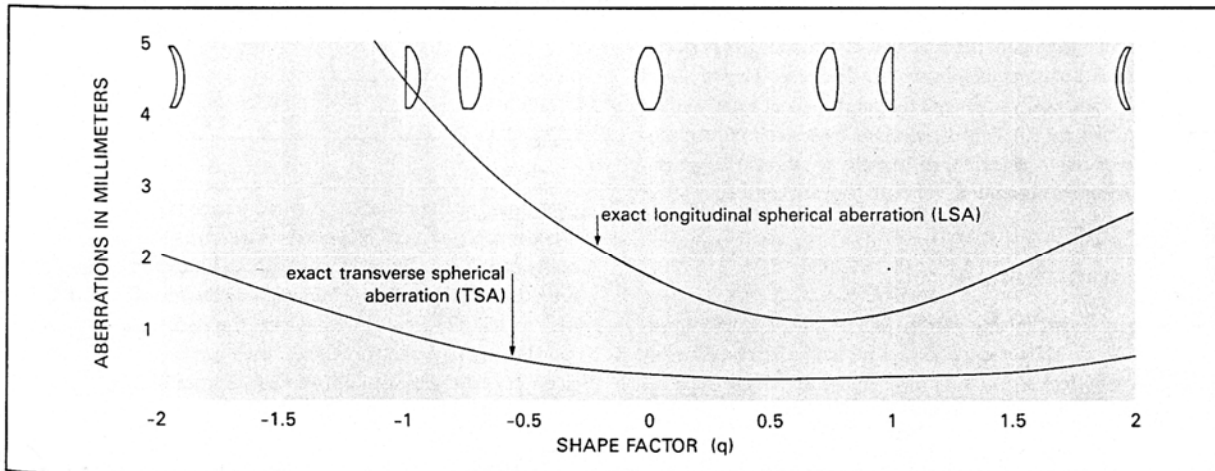


## Lens Shape

- Coddington 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

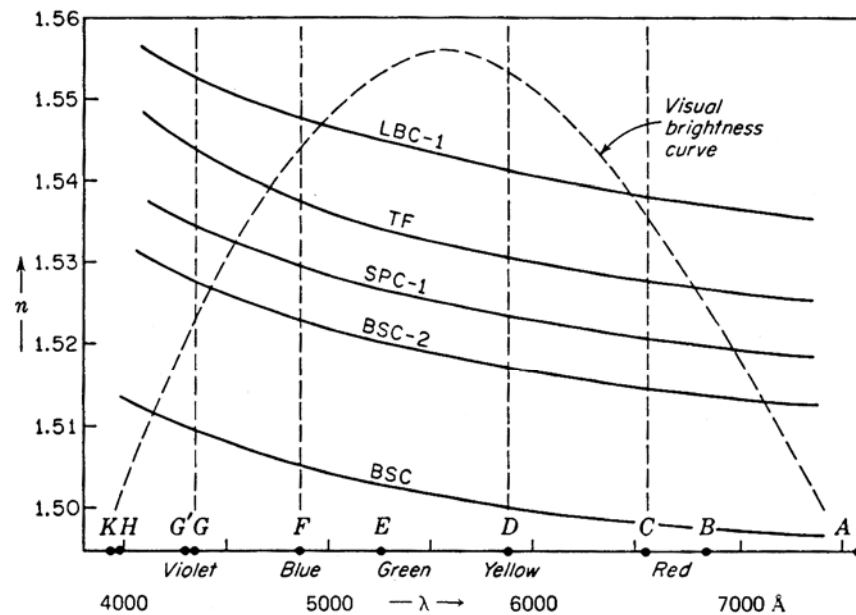


FIGURE 9Y

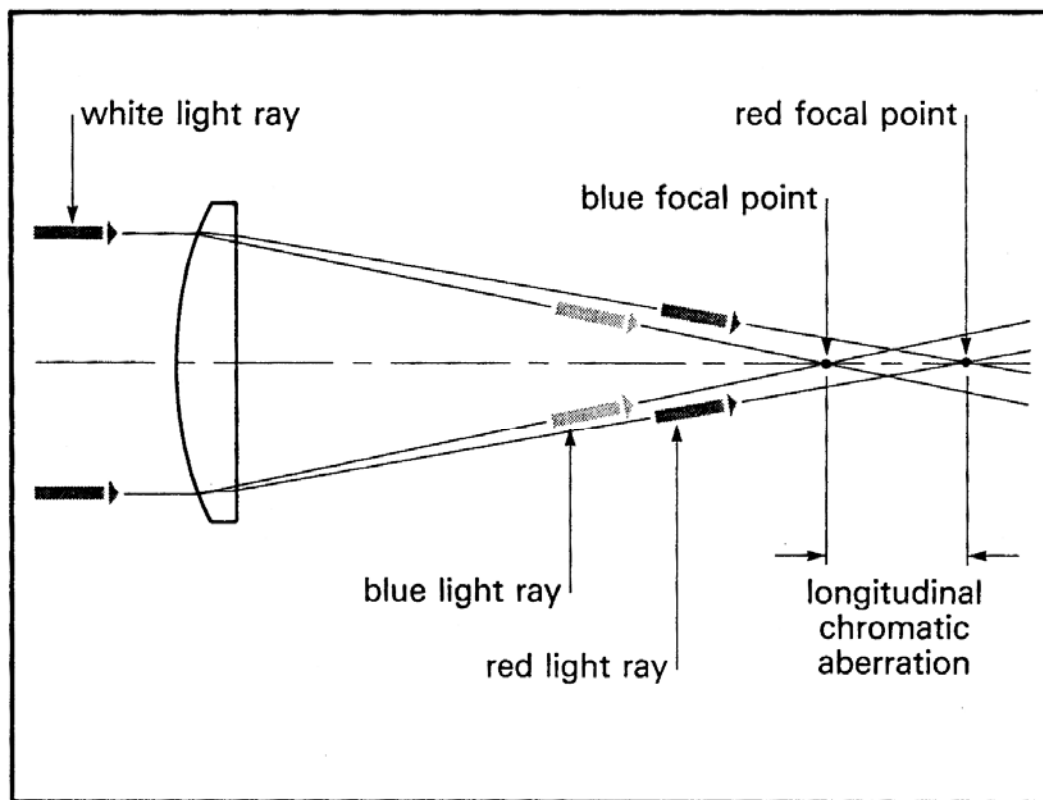
Graphs of the refractive indices of several kinds of optical glass. These are called dispersion curves.

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

| Medium                 | Designation      | ICT type | $\nu$ | $n_C$   | $n_D$   | $n_F$   | $n_G$   |
|------------------------|------------------|----------|-------|---------|---------|---------|---------|
| 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 <sub>2</sub> |          | 67.9  |         | 1.4585  |         |         |
| Crystal quartz (O ray) | SiO <sub>2</sub> |          | 70.0  |         | 1.5443  |         |         |
| Fluorite               | CaF <sub>2</sub> |          | 95.4  |         | 1.4338  |         |         |

## Chromatic Aberration

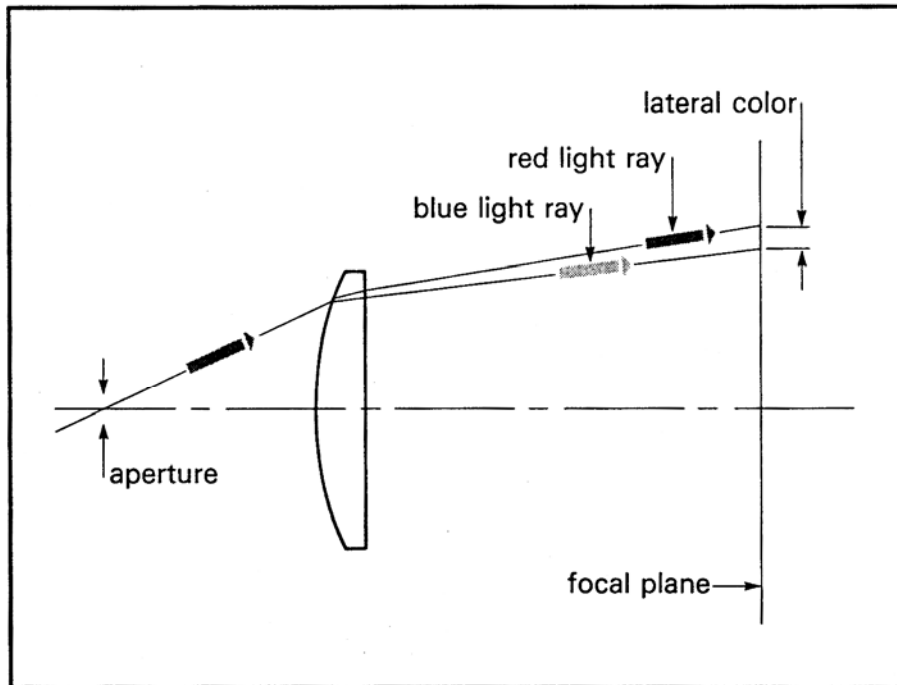
- Chromatic Aberrations
  - different wavelength focus to different points
- Due to index of refraction change with wavelength
- Hence focuses rays at different points
- Generally blue closer (higher  $n$ )  
Red further away (lower index)
- Important for multiline lasers
- Achromatic lenses: combine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



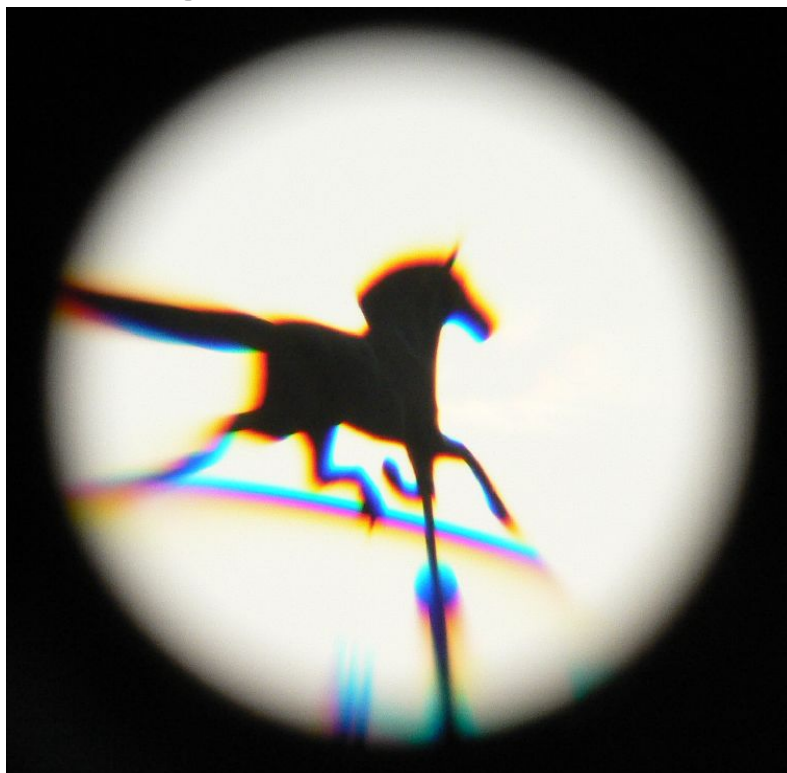
**LONGITUDINAL CHROMATIC ABERRATION.**

## Lateral Colour Aberration

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

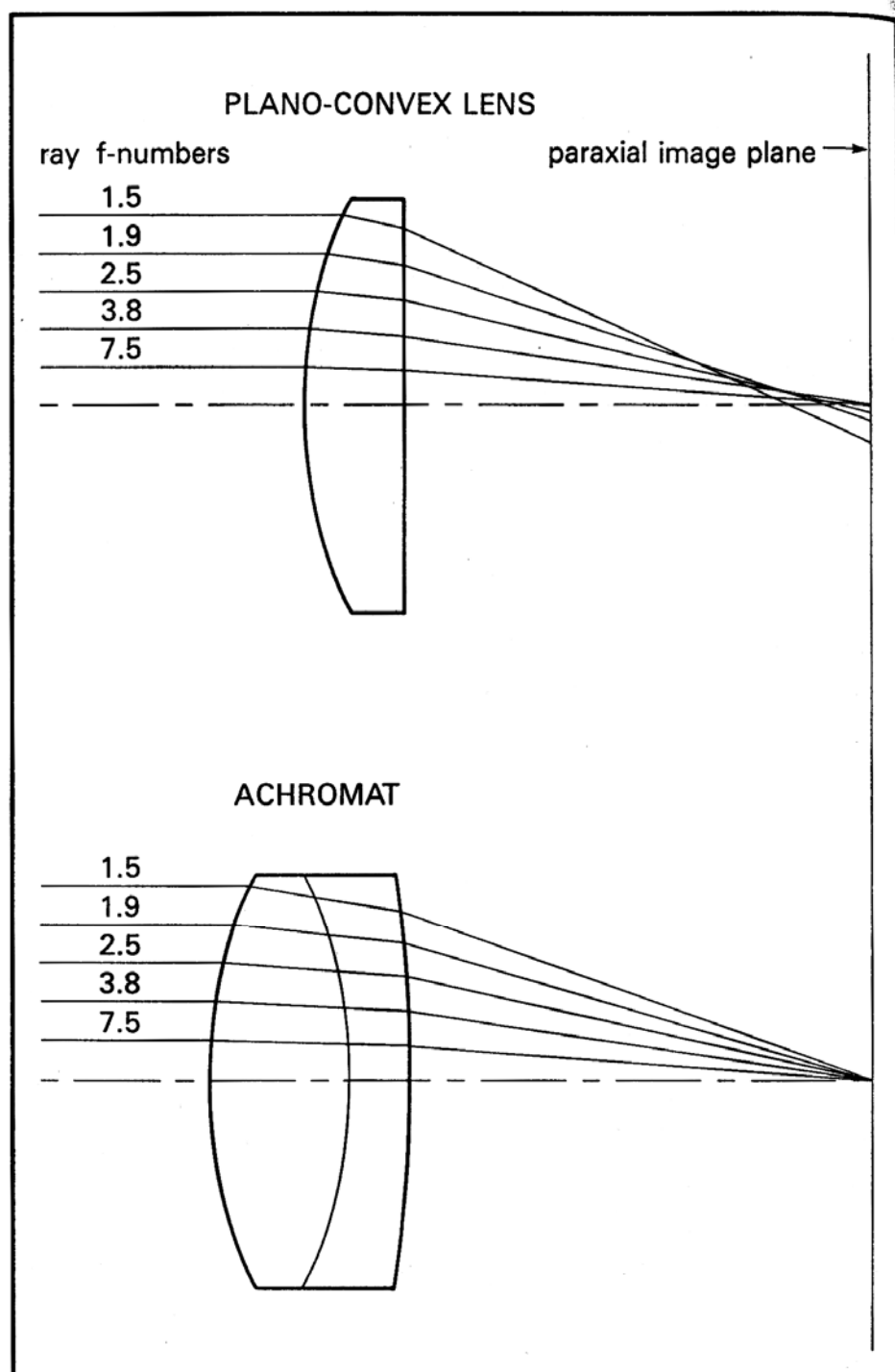


**LATERAL COLOR** is the difference in image height between red and blue rays.



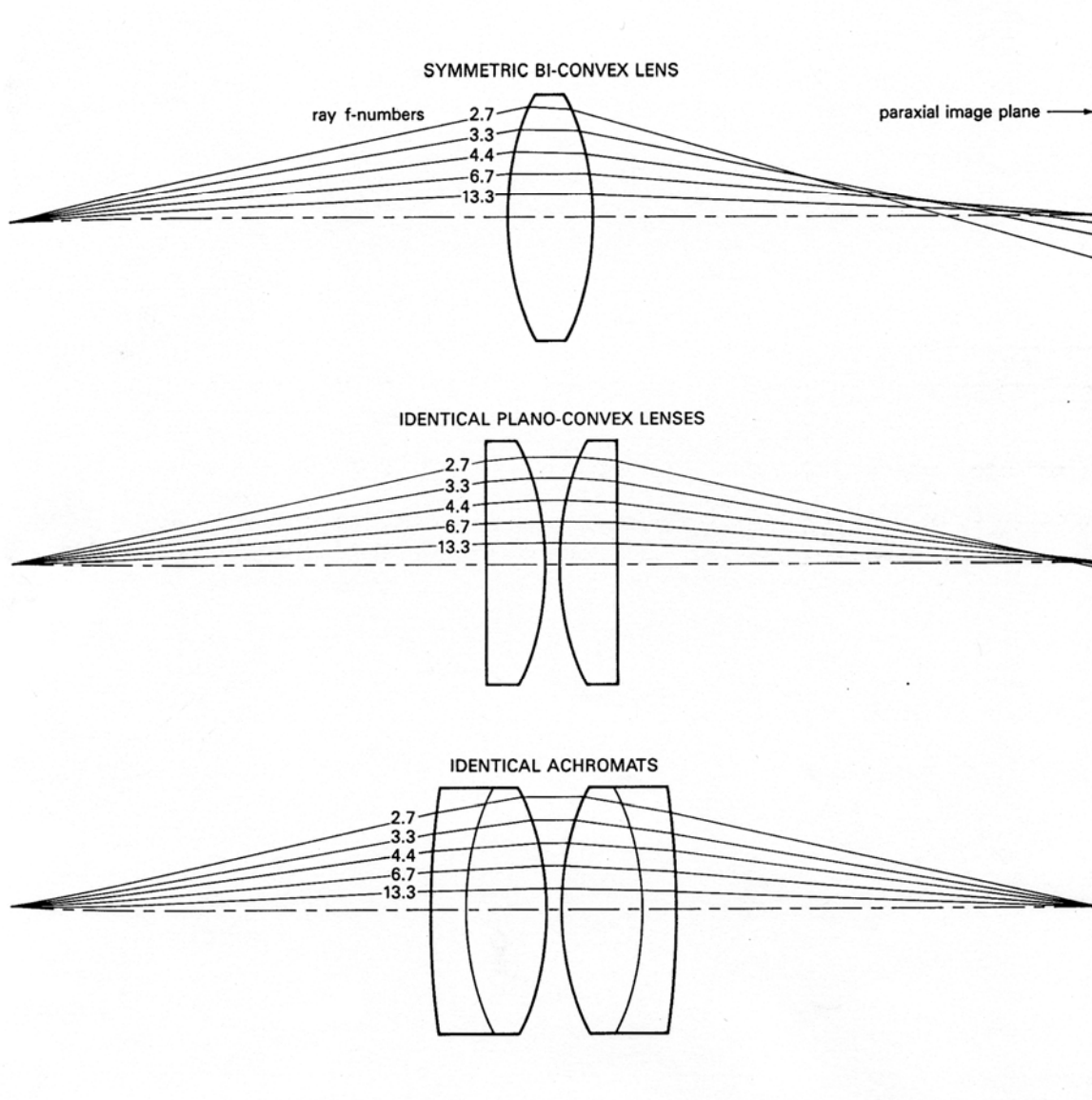
## Singlet vs Achromat Lens

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



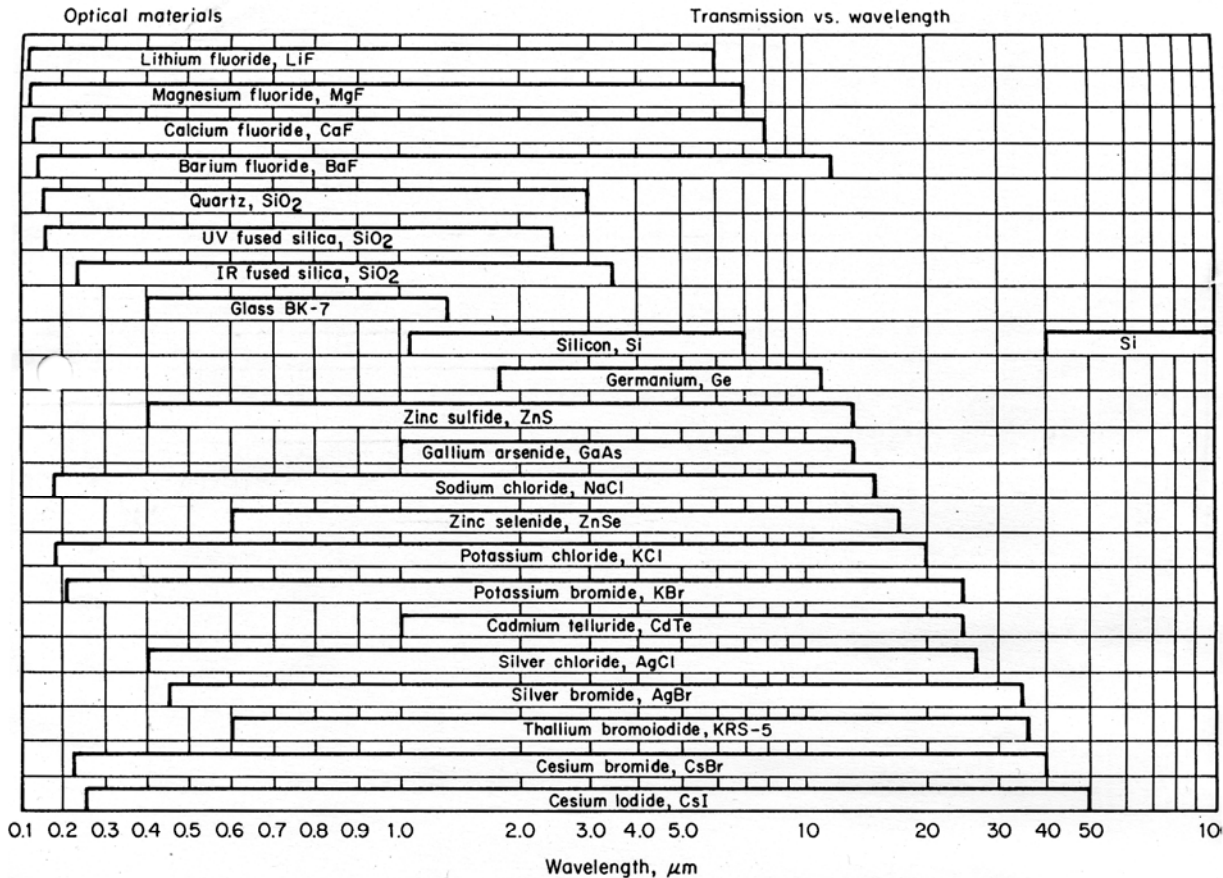
## Combined lens: Unit Conjugation

- 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 Fluoride
- 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 Japax Technology Inc.)