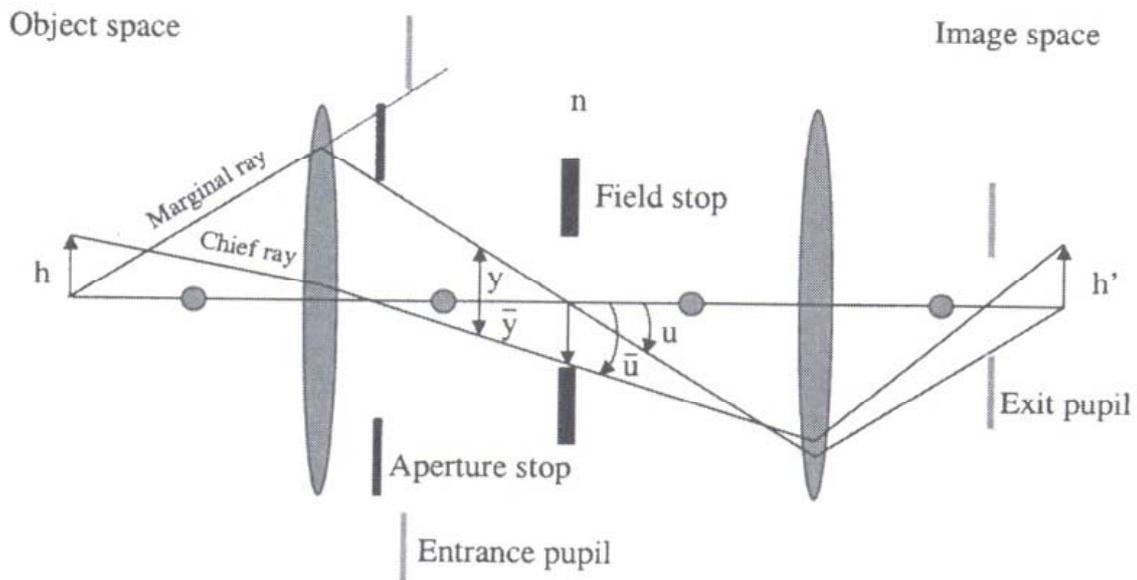


# Astronomische Waarneemtechnieken (Astronomical Observing Techniques)

6<sup>th</sup> Lecture: 22 October 2008



Based on "Astronomical Optics" by Daniel J. Schroeder, "Principles of Optics" by Max Born & Emil Wolf, and the "Optical Engineer's Desk Reference" by William L. Wolfe.

## Part I Geometrical Optics

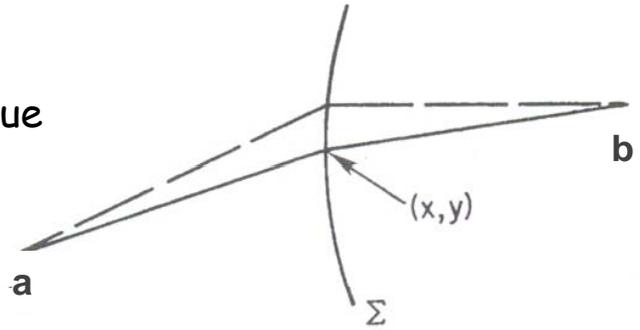
## Part II Diffraction Optics

# Fermat's (General) Principle

Consider two points, a and b, and various paths between them. The travel time between them is  $\tau$ .

Condition:  $\tau$  will have a stationary value

for the actual path:  $\frac{\partial \tau}{\partial x} = \frac{\partial \tau}{\partial y} = 0$



Equivalently: travel time  $\Leftrightarrow$  optical path length (OPL)

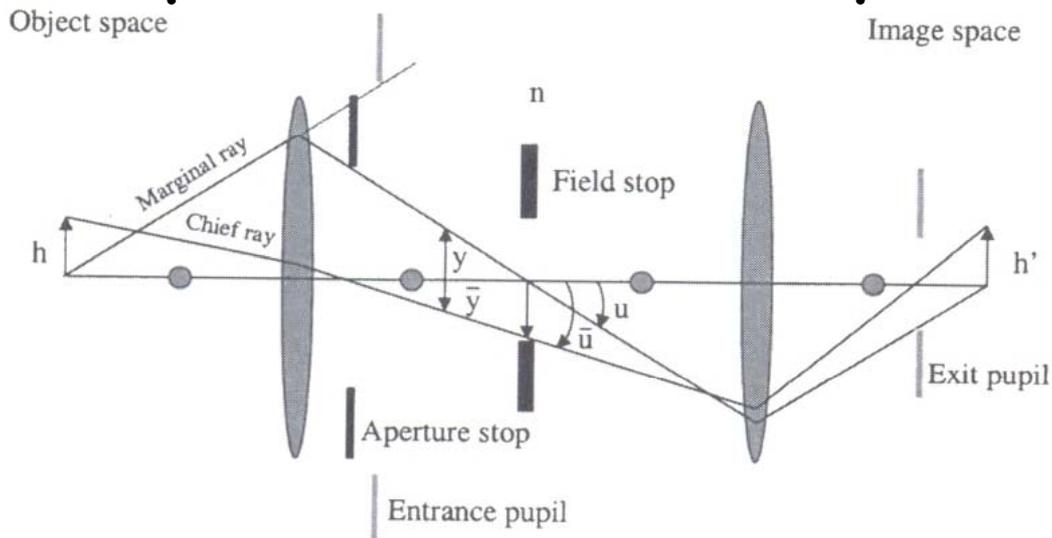
$$d(\text{OPL}) = c dt = \frac{c}{v} \cdot v dt = n \cdot \frac{ds}{dt} dt = n ds$$

$$\text{OPL} = \int_a^b n ds$$

where  $v$  is the speed of light in the medium of index  $n$ .

Fermat's principle states that the OPL is the shortest distance  $a \rightarrow b$

## Aperture and Field Stops



**Aperture stop:** determines the diameter of the light cone from an axial point on the object.

**Field stop:** determines the field of view of the system.

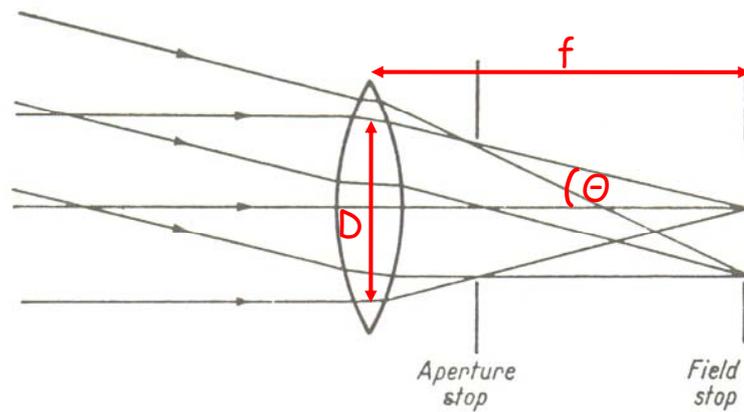
**Entrance pupil:** image of the aperture stop in the object space

**Exit pupil:** image of the aperture stop in the image space

**Marginal ray:** ray from an object point on the optical axis that passes at the edge of the entrance pupil

**Chief ray:** ray from an object point at the edge of the field, passing through the center of the aperture stop.

# The Speed of the System



The speed of an optical system is described by the **numerical aperture NA** and the **F number**, where:

$$NA = n \cdot \sin \theta \quad \text{and} \quad F \equiv \frac{f}{D} = \frac{1}{2(NA)}$$

Generally, **fast optics** (large NA) has a high light power, is compact, has low tolerances and is difficult to manufacture. **Slow optics** (small NA) is just the opposite.

## Aberrations

Generally, aberrations are departures of the performance of an optical system from the predictions of paraxial optics and lead to blurring of the image. There are two categories of aberrations:

1. **On-axis aberrations** (defocus, spherical aberration)
2. **Off-axis aberrations** (coma, astigmatism, distortion, ...)

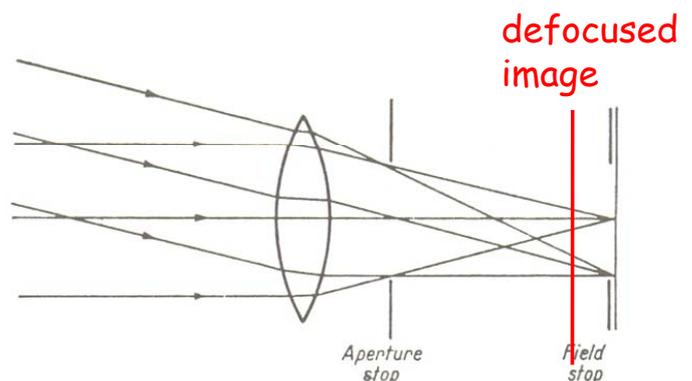
## Defocus

**Defocus** means "out of focus".

The amount of defocus can be characterized by the **depth of focus**\*

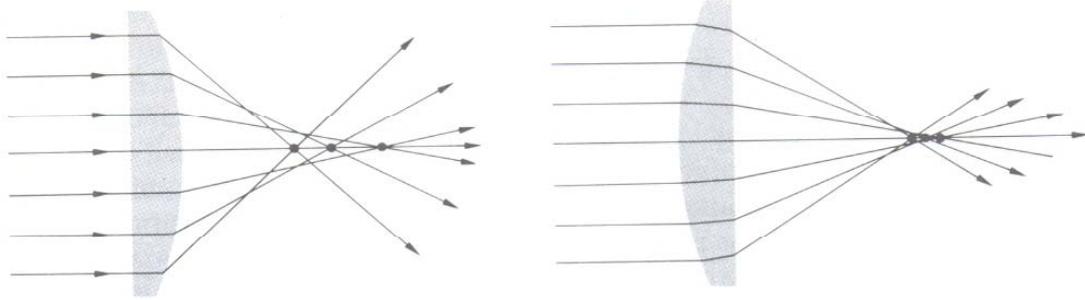
$$\delta = 2\lambda F^2 = \frac{\lambda}{2} \left( \frac{1}{NA} \right)^2$$

\*the depth of focus usually refers to an optical path difference of  $\lambda/4$ .



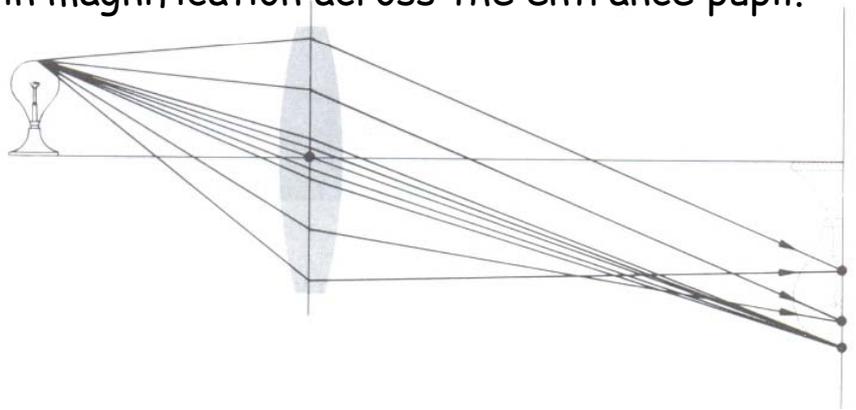
# Spherical Aberration

Rays further from the optical axis have a different focal point than rays closer to the optical axis



## Coma

Coma appears as a variation in magnification across the entrance pupil. Point sources will show a cometary tail.



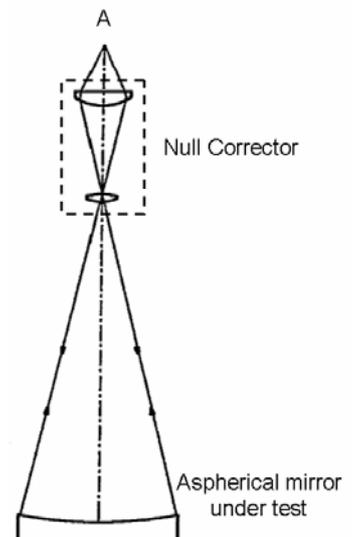
## Side note: The Spherical Aberration of HST

Optical problem: **HST primary mirror** suffers from spherical aberration.

Reason: the null corrector used to measure the mirror shape had been incorrectly assembled (one lens was misplaced by 1.3 mm).

Management problem: The mirror manufacturer had analyzed its surface with other null correctors, which indicated the problem, but the test results were ignored because they were believed to be less accurate.

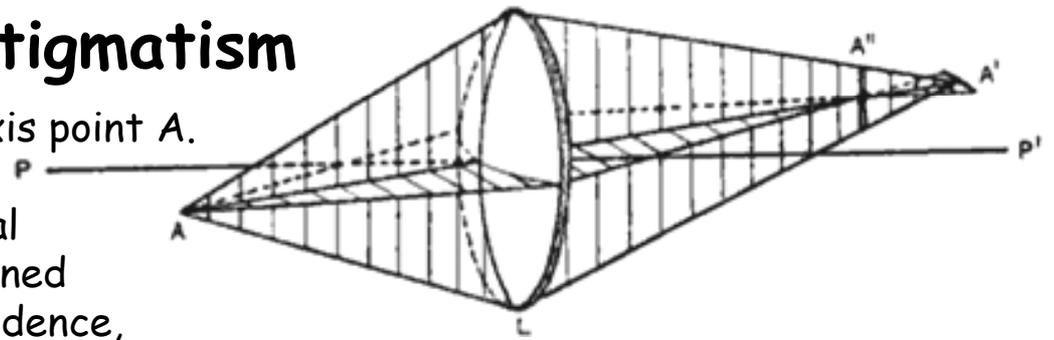
*A **null corrector** cancels the non-spherical portion of an aspheric mirror figure. When the correct mirror is viewed from point A the combination looks precisely spherical.*



# Astigmatism

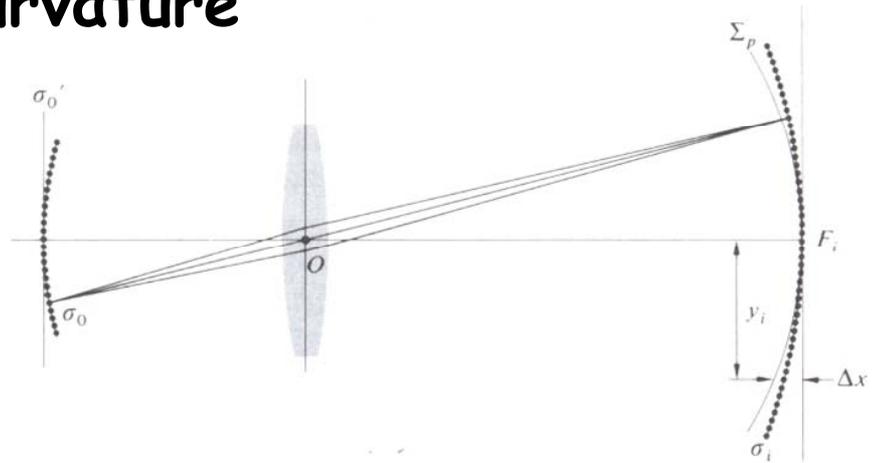
Consider an off-axis point  $A$ .  
The lens does not appear symmetrical from  $A$  but shortened in the plane of incidence,

the **tangential plane**. The emergent wave will have a smaller radius of curvature for the tangential plane than for the plane normal to it (sagittal plane) and form an image closer to the lens



# Field Curvature

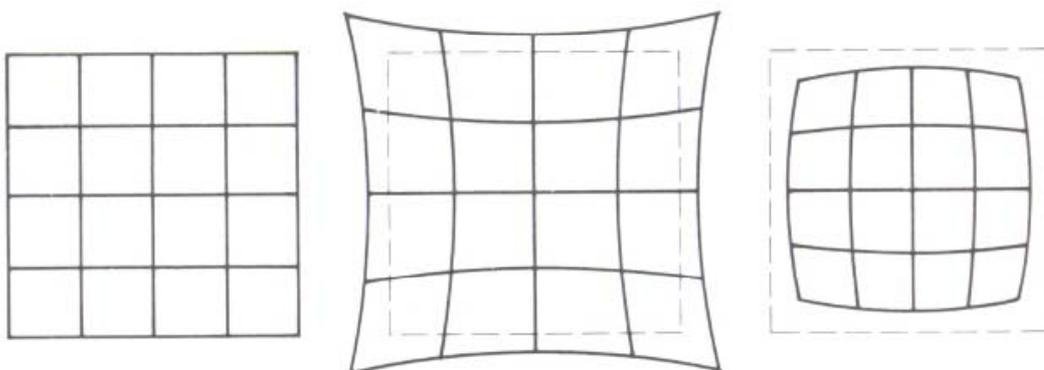
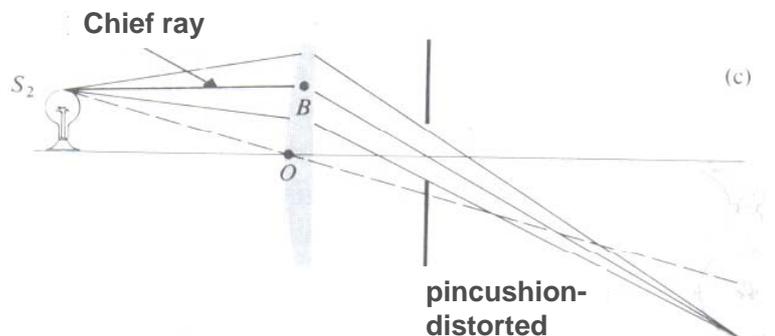
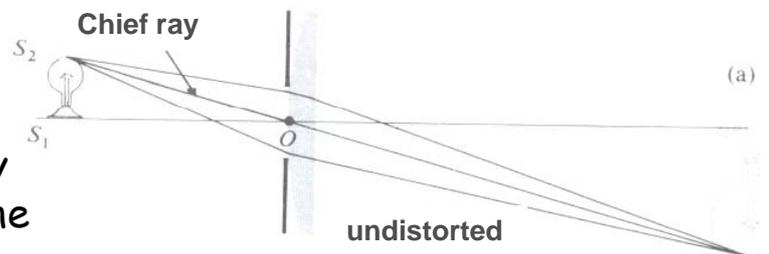
Only small objects (close to the optical axis) can be considered "flat". Close-to-axis and far off-axis objects will have different focal points due to the OPL difference.



# Distortion

The transversal magnification may not be constant but depends on the distance from the optical axis. Generally there are two cases:

1. Outer parts have smaller magnification  $\rightarrow$  **barrel distortion**
2. Outer parts have larger magnification  $\rightarrow$  **pincushion**



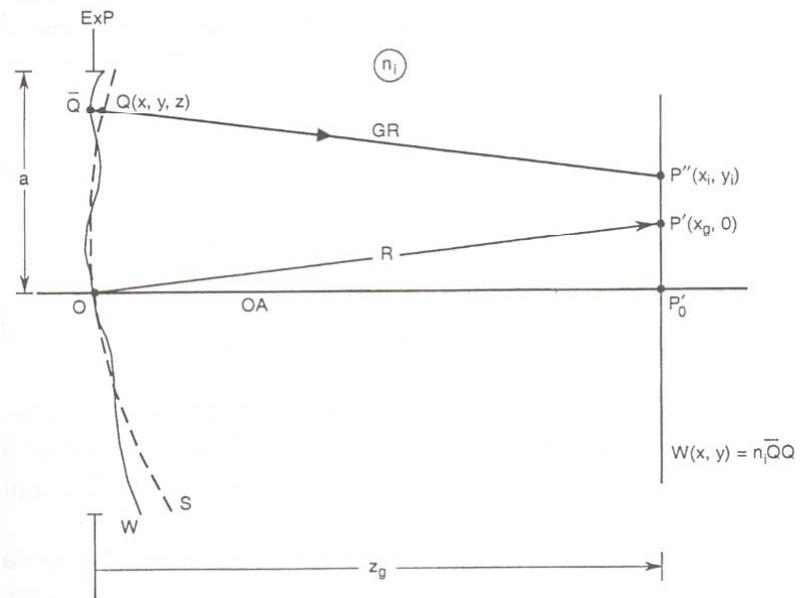
# Relation between Wave and Ray Aberrations

Consider a reference sphere  $S$  of curvature  $R$  for an off-axis point  $P'$  and an aberrated wavefront  $W$ .

An "aberrated" ray from the object intersects the image plane at  $P''$ .

The ray aberration is  $P'P''$ .

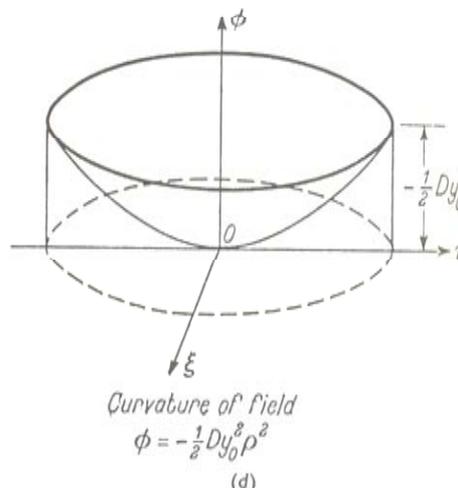
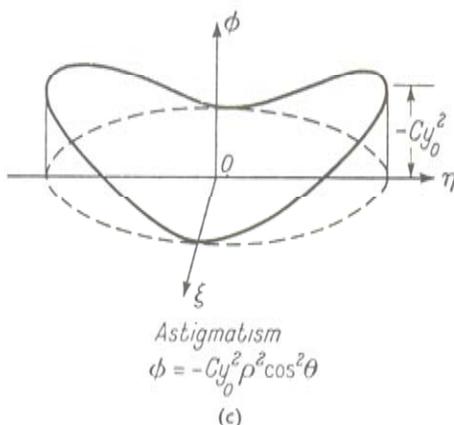
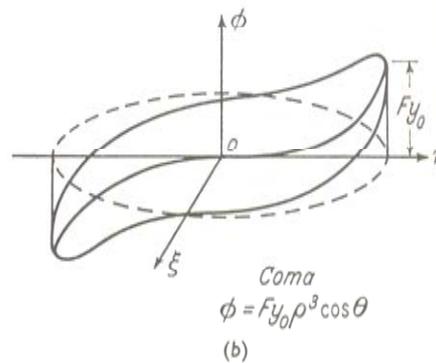
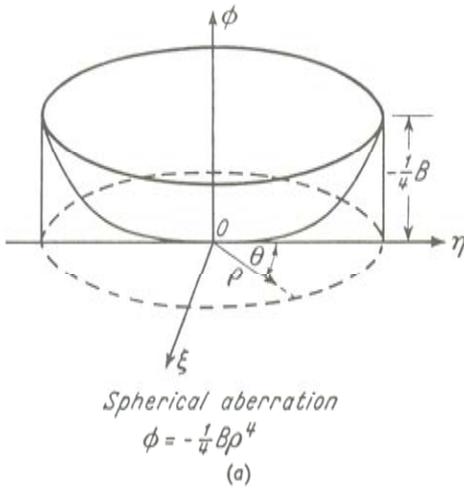
The wave aberration is  $n \cdot \bar{Q}Q$



For small FOVs and a radially symmetric aberrated wavefront  $W(r)$  we can approximate the intersection with the image plane:

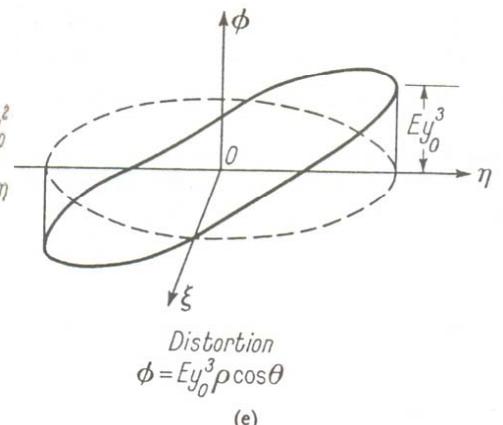
$$r_i = \frac{R}{n_i} \frac{\partial W(r)}{\partial r}$$

## The Primary Wave Aberrations



Notes:

- $\phi$  is the wave aberration
- $\Theta$  is the angle in the pupil plane
- $\rho$  is the radius in the pupil plane
- $\xi = \rho \sin \Theta$ ;  $\eta = \rho \cos \Theta$
- $y_0$  = position of the object in the field



Part I

Geometrical Optics

Part II

Diffraction Optics