Petzval Lens

- Enter Petzval, a Hungarian mathematician. To pursue a prize being offered for the development of a wide-field fast lens system he enlisted Hungarian army members seeing a distraction from calculating the trajectories of artillery shells. After 6 months of calculation they arrived at the “Petzval” lens configuration.

- Ironically the Chevalier lens was awarded the prize despite the superiority of the Petzval system.
Petzval Lens

**Figure 9.8.** Petzval lens with field flattener.

Fundamental Optical Design (Kidger)
Thick Lenses

- A true lens - as opposed to the idealization of a thin lens - consists of two separated refractive boundaries.
- The lens' focal length is not measured from the lens center, but from the "principal plane."
- The principal plane is different depending on the direction of propagation through the lens, and represents the location of a thin lens of equivalent focal length as indicated by the intersection of the parallel rays from infinity entering the system with the convergent rays following the lens.
- This concept of a principal plane can be generalized to any optical system.
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**Thick Lenses**

[Diagram showing ray paths and focal lengths for thick lenses, with labels indicating relationships and calculations.]
Classical Optical Solutions

Fig. 1.6 Map showing the design types which are commonly used for various combinations of aperture and field of view. (From W. Smith, Modern Lens Design (McGraw-Hill, 1992). Reprinted with permission of the McGraw-Hill companies.)
A "classical" Cassegrain reflector consists of a parabolic primary (conic constant = -1.0) and a hyperbolic secondary mirror.

The secondary will (re)-introduce spherical aberration unless it has a conic given by

\[ K_2 = -\left(\frac{m + 1}{m - 1}\right)^2 \text{ where } -m = \frac{d + b}{D_2} \]

Fig. 7.1 Typical Layout of a Cassegrain Telescope.
Ritchie-Chretien Telescopes

- Parabolas and classical Cassegrain telescopes suffer coma.
- A two mirror telescope with two aspheric surfaces has sufficient degrees of freedom to compensate for both Spherical Aberration and Coma.
- An "aplanatic Cassegrain" (a.k.a. a Ritchey-Chretien) configuration will be coma free if
  
  \[ K_1 = -1 - \frac{2(1 + \beta)}{m^2(m - \beta)} \]

  \[ K_2 = - \left( \frac{m + 1}{m - 1} \right)^2 - \frac{2m(m + 1)}{(m - \beta)(m - 1)^3} \]  
  where  \( \beta = \frac{d + b}{f_1} \)

- The primary and secondary are both hyperbolic in Ritchie-Chretien configuration.
- The elimination of coma means that this configuration has better off-axis performance than the classical cassegrain

- Ritchey-Cretien designs are preferred for wide-field applications.
Off-axis Comparison

- The RC design has non-existent coma and is superior at small off-axis distances.
- At off-axis extremes the Classical and RC results converge due to the dominance of astigmatism.
Stops and Pupils

• Stops serve two primary functions:
  
  • **Aperture stops** constrains the amount of light that can pass through a system – the simplest being a stop limiting the entrance aperture of a telescope.
  
  • **Field stops** directly limit the observable field of view – the simplest being a mask directly in front of a detector.
Stops and Pupils

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  - **Field stops** directly limit the observable field of view – the simplest being a mask directly in front of a detector.

- A system will have one surface - be it a lens radius or a dedicated stop - which serves to limit the passage of rays.
  - This stop may lie at a physically obvious location (e.g. the aperture of a telescope).
  - Alternatively, the stop may be physically interior to the system and its images relayed by the optics define the entrance and exit pupils for the system.
Fig. 5.8 Images of stop: a. the entrance pupil; b. the exit pupil. From M. Klein, Optics (John Wiley and Sons). Reprinted with permission of John Wiley and Sons, Inc.

Introduction to Lens Design (Geary)

Fig. 5.9 Real ray bundle appears limited by virtual entrance pupil. From M. Klein, Optics (John Wiley and Sons). Reprinted with permission of John Wiley and Sons, Inc.
Re-imaged Stops as Entrance and Exit Pupils

- In a simple telescope the objective defines the entrance aperture.
  - The eyepiece produces an image of the entrance aperture – the exit pupil.
    - This is the minimum radius for the bundle of rays leaving the system from all field angles and represents the ideal location for the eye.
    - The pupil size should be smaller than the dark adapted eye's pupil and it should be located sufficiently far from the last optic that there is room for the eye (eye relief).

Figure 3 - Formation of the exit pupil in an eyepiece.
Controlling Aberrations with Stops

- Since spherical aberration is zonally dependent, introducing an aperture stop will reduce the spherical aberration of a system.
  - not practical in astronomy since this means throwing away aperture/light.

Fig. 6K. Spherical aberration of a concave spherical mirror.
Controlling Aberrations with Stops

- The lensless Schmidt camera is a vivid example of a practical stop application.
  - Here the stop is located at the center of curvature of the primary mirror.
- Rays from a given field angle illuminate a portion of the primary as on-axis rays.
  - The slow f/# ensures that spherical aberration is small. No off-axis aberrations exist because, technically, no rays are off axis.
  - Curvature of field is significant, however.

*Figure 1. The optical layout of the lensless Schmidt camera.*

http://home.freeuk.com/m.gavin/schmidt_lens.htm
Controlling Aberrations with Stops

- In practice a corrector plate enables a “fast” system configuration that more efficiently uses the primary mirror.

http://oemagazine.com/fromTheMagazine/aug05/designdesk.html
Baffling

- Optical systems can propagate unwanted rays to the focal plane.
- Most surfaces are mirror-like at grazing incidence.

Fig. 19.5 Stray Light in an Unbaffled Cassegrain.
Baffling

- Optical systems can propagate unwanted rays to the focal plane.
- Most surfaces are mirror-like at grazing incidence.

- Introduce surfaces to block unwanted rays directly
Interior surfaces and baffles must be painted to suppress stray light. Ideally these surfaces have zero reflectance at
- all wavelengths
- all angles of incidence
Perfect paints are difficult to find in practice.
Visually black paints may be reflective at infrared wavelengths
Interior surfaces and baffles must be painted to suppress stray light. Ideally these surfaces have zero reflectance at
  - all wavelengths
  - all angles of incidence
Perfect paints are difficult to find in practice.
  - Visually black paints may be reflective at infrared wavelengths

Fig. 7-40. The spectral absorption of Lampblack Paint, Parson’s Black Gold-Black, and BEC-1,2,3, and 4. (BEC = Barnes Engineering Co.) [7-24].
Paints

The Infrared Handbook (Wolfe)

Fig. 7-41. The spectral absorption of 3M black and Cat-A-Lac black at 77 and 373 K. Cat-A-Lac® is a registered trademark of Bostic-Finch, Inc. [7-23].

Fig. 7-42. The spectral absorption of Sicon black at 77 and 373 K. Sicon® is a registered trademark of Midland Industrial Finishes [7-23].
Infrared Camera Design

- Mirrors vs. Lenses
- Basic properties of refractive materials
- Considerations for camera design
  - field of view, wavelengths, pixel size
  - operating temperature
  - instrument volume
  - system throughput
- Example cameras - an Eric Persson extravaganza
  - PASP v. 104, p. 204.
  - PASP v. 107, p. 1234
  - Astron.J. v. 124, p. 619
Mirrors vs. Lenses

- Light can be focused either by mirrors or by lenses.
  - Both have their advantages and disadvantages
- Mirrors can have high reflectivity (good throughput) especially at infrared wavelengths
  - Gold mirror coatings are nearly 99% reflective across the infrared
    - Limited penalty for “folded” designs
- Mirrors do not suffer chromatic aberration
- Aspheric mirrors can control Seidel aberrations
  - but alignment can be touchy -- mirrors tend to enhance alignment errors, lenses are more forgiving.
7.4.4. Reflectors. Although in the infrared most metal mirror surfaces are better than at shorter wavelengths, the requirements are often very stringent. Representative spectral curves are given in Figure 7-43. The reader should be aware that oxidation, dust, and tarnish from other chemical reactions can reduce the reflectivity of the specified surfaces below that reported here.

Fig. 7-43. The reflectance of various films of silver, gold, aluminum, copper, rhodium, and titanium [7-75].
Basic Properties of Infrared Refractive Materials

- Wavelength transmission
  - Short wavelength cutoff set by electronic absorption
  - Long wavelength cutoff set by lattice absorption – phonons

- Optical properties / Refractive index
  - Fresnel reflection / need for AR coatings
  - Dispersion (introducing/controlling chromatic aberration)
  - Temperature dependence of optical properties (and documentation thereof) – cryogenics
  - Visible wavelength transmission (alignment)

- Mechanical properties
  - “Machinability” (crystalline vs. amorphous materials)
  - thermal expansion / fragility
  - hygroscopic tendencies
Wavelength Transmission of Common Materials
The Transmission of Glasses
Infrared Optical Materials

- Short wavelength cutoff from electronic absorption across an insulator's "bandgap"
- Long wavelength cutoff from phonon excitation in crystal lattice (normal modes of the crystalline structure).

- Materials vary in cost, durability, availability.
- For example, Calcium Fluoride transmits from 0.13-12 microns -- overkill for a 1-2.5um camera?.
  - It is commonly used, however, because it is inexpensive, easily polished, and fairly durable.
Specific Infrared Materials

**QUARTZ, FUSED SILICA (SiO₂)**

Fused Silica is used for windows, lenses in the .16-2.5 micron range. It is available in IR & UV grade, depending on your requirements. It is good for high temperature and strength applications.

**CALCIUM FLUORIDE:**

CaF₂ is used for optical windows, lenses and prisms in .15-9 micron range. Because of its low absorption at wavelength shorter than 6 microns, CaF₂ is particularly popular for high power laser optics in that wavelength range. Due to its low refractive index it can be used without anti-reflection coating.

**FUSED SILICA (Quartz)**

- Usefull Transmission Range: 0.2 - 2.5 μ
- Reflection Losses: 6.3% for 2 Surfaces @ 2μ
- Refractive Index: @ .5890 μ = 1.4584
- Rupture Modulus: = 7110 psi

**CALCIUM FLUORIDE**

- Usefull Transmission Range: 0.13 - 8.0 μ
- Reflection Losses: 5.6% for 2 Surfaces @ 4.0μ
- Refractive Index: @ 5 μ = 1.400
- Rupture Modulus: = 5300 psi
Specific Infrared Materials

Germanium:

Ge is a versatile IR material used commonly in imaging systems and instruments in 2-14 micron region for lenses, windows and output couplers for low power CW as well as pulsed TEA CO₂ lasers. Ge is limited to thruput power range of 50-100 watts before the onset of significant thermal lensing or thermal runaway. Ge is non hygroscopic and has good thermal conductivity, excellent surface hardness and good strength.

\[
\text{reflected fraction} = \left( \frac{n - 1}{n + 1} \right)^2
\]

\[
\begin{align*}
\mathcal{E}_o & \rightarrow \mathcal{E}_1 \\
\mathcal{E}_2 & \rightarrow \mathcal{E}_3 \\
N = 1 & \\
N = 1.38 & \\
N = 1.52 & \\
r_{12} = 0.160 & \\
r_{23} = 0.048 & 
\end{align*}
\]

GERMANIUM

Absorption Coefficient: \(< 0.03 \text{cm}^{-1} @ 10.6 \mu\)

Useful Transmission Range: \(2 - 14 \mu\)

Reflection Losses: 53\% for 2 Surfaces @ 10 \(\mu\)

Refractive Index: @ 10.6 \(\mu = 4.0029\)

Rupture Modulus: = 10,500 psi
Specific Infrared Materials

SILICON:

Si is a very useful IR material in 3-5 micron atmospheric window where many Infrared Avionics systems are operational. Optical grade polycrystalline Si is used to make lenses, domes and windows, etc.

Because of its high thermal conductivity it is also very good mirror substrate for high power lasers.

Barium Fluoride:

BaF$_2$ is used for optical windows, lenses and prisms in 2-11 micron range. The material is very hard but is very sensitive to thermal shock.

**SILICON**
- Absorption Coefficient: $0.10 \text{cm}^{-1} @ 5.0 \mu\text{m}$
- Useful Transmission Range: $1.2 - 8 \mu\text{m}$
- Reflection Losses: $46\%$ for 2 Surfaces @ $10 \mu\text{m}$
- Refractive Index: $n = 3.4184$
- Rupture Modulus: $= 19,000$ psi

**BARIUM FLUORIDE**
- Useful Transmission Range: $0.15 - 11.5 \mu\text{m}$
- Reflection Losses: $6\%$ for 2 Surfaces @ $4.0 \mu\text{m}$
- Refractive Index: $n = 1.461$
- Rupture Modulus: $= 3900$ psi
Specific Infrared Materials

**ZINC SULFIDE:**

CVD produced ZnS comes in 2 grades. The regular grade is useful for FLIR applications and has good transmission in 1-12 micron range, with reasonable hardness and good strength.

The other grade water-clear ZnS called Cleartran (trademark of CVD, Inc.) transmits not only in the infrared but also in the visible in the .4 to 12 micron range.

**Zinc Selenide:**

CVD produced ZnSe transmits very well from .6 microns in the visible to 15 microns in the infrared. Due to its low absorptivity at several laser wavelengths ZnSe is excellent in many laser systems for lenses, windows, output couplers and Beam splitters. Because of its broad transmission range and specifically its low absorption and scatter in the 8-14 micron region, ZnSe is a standard material for use in FLIR and other infrared instrument or imaging systems. ZnSe is non-hygroscopic, chemically stable unless treated with strong acids, and safe to use in industrial and field applications as well as laboratory environments.

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**ZINC SULFIDE**

- **Useful Transmission Range:** .4-12µ
- **Reflection Losses:** 30%
- **Refractive Index:** 2.2 at 10.6
- **Rupture Modulus:** 15,000 psi

**ZINC SELENIDE**

- **CVD Processed**
- **Absorption Coefficient:** <0.005 cm⁻¹ @ 10.6 µ
- **Useful Transmission Range:** .6 - 18µ
- **Reflection Losses:** 30% for 2 Surfaces @ 10.6 µ
- **Refractive Index:** @ 10.6 µ = 2.400
- **Rupture Modulus:** = 8500 psi
Specific Infrared Materials

**KRS-5:**

KRS-5 is used for lenses, windows and prisms for applications from .6 micron to 50 microns. It is relatively insoluble in water and may be used in cells in contact with aqueous solutions.

**ARSENIC TRISULFIDE (As$_2$S$_3$):**

Arsenic Trisulfide glass is an inexpensive Infrared material, which is somewhat transparent in the visible and goes out to 9 microns. It is used to make lenses and windows for IR thermometer and other instruments.

---

**THALLIUM BROMOIODIDE**

- Useful Transmission Range: 0.6 - 40 μ
- Reflection Losses: 28.4% for 2 Surfaces @ 10 μ
- Refractive Index: @ 10 μ = 2.371
- Rupture Modulus: = 3800 psi

**ARSENIC TRISULFIDE**

- Useful Transmission Range: 0.8 - 10 μ
- Reflection Losses: 28.5% for 2 Surfaces @ 10 μ
- Refractive Index: @ 6 μ = 2.403
- Rupture Modulus: = 2400 psi
Camera Design
Camera Design Considerations - Wavelength

- Wavelength choice is certainly science driven, but constrained by the practicalities of
  - detector response
  - available detector format
  - field of view
  - cryogenics
  - optical materials
  - ambient backgrounds
  - atmospheric transmission
Ambient Backgrounds -- Thermal Emission

- In any environment -- ground or space -- thermal emission of the optical surfaces and ambient environment constrains scientific choices.
- On the ground (at night), 300K blackbody emission becomes dominant longward of 2um -- even for 1% emissivity mirrors.
- In daylight, Rayleigh scattering thwarts visible and near-infrared observation but is not competitive with thermal emission beyond 3um.

Fig. 2.3. *Left:* Day sky background. A–E, scattered sunlight for various altitudes and conditions; F is a blackbody at 283K; G is emission of water vapor and CO$_2$; H = bright aurora; I, J = haze radiance + scatter of Earth flux under different conditions. *Right:* Night sky background. J, city lights; A, blackbody at 283K; B, emission of water vapor and CO$_2$; C, aurora; D, airglow; E, F, haze and scatter of Earth flux under different conditions; G–K, scattered moonlight for various conditions; from Stewart and Hopfield (1965).
Ambient Backgrounds -- Airglow Emission

- Even at near-infrared wavelength where thermal emission is negligible, atmospheric airglow emission contaminates broadband observations.
- Airglow arises from molecular emission, particularly OH-, excited by daylight in the upper atmosphere (80km).

Fig. 2.5. Airglow emission in the H-band; from Ramsey, Mountain and Geballe (1992).
Ambient Backgrounds -- Airglow Emission

- The astronomical H-band (1.6\,\mu m) contains the worst airglow contamination, although no band escapes some effect from airglow.

Here J- and H-bands are compared on the same vertical scale.

Fig. 2.4. Airglow emission in the J-band; from Ramsey, Mountain and Geballe (1992). The region around 1.4\,\mu m was not measured.

Fig. 2.5. Airglow emission in the H-band; from Ramsey, Mountain and Geballe (1992).
Ambient Backgrounds -- Airglow Emission

- Airglow is time variable. Some components can be worst in the evening due to solar excitation. The primary component lingers throughout the night.

- Airglow intensity can change by 20-30% in 10 minutes and can double in an hour.

- Airglow has structure on arcminute scales.

Airglow monitoring in the infrared
Ambient Backgrounds -- Space Observatories

- In space, telescopes can be cooled to near absolute-zero temperature.

- A ground-based 10 meter telescope would require 20 days of integration to equal the 8μm sensitivity of a 12 second integration with the 85cm Spitzer telescope.

- The space environment is not immune to ambient background. Zodiacal emission, Galactic cirrus, and the Cosmic Microwave Background place fundamental limits on sensitivity.

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Fig. 2.7. Specific intensity ($\times \nu$) of diffuse emission from the night sky, observed away from the galactic and ecliptic planes, from high in the Earth's atmosphere; from Leinert et al. (1998). Mainly derived from COBE data.