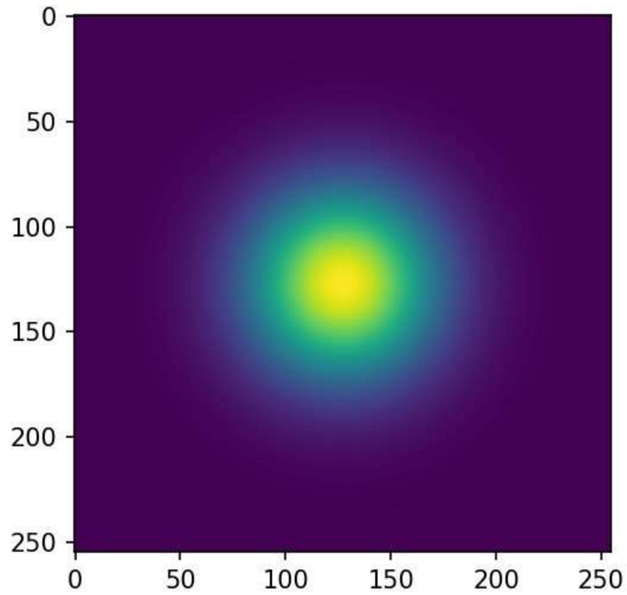
2 Beating the atmosphere

Taking image of point-like astronomical sources:
Represented by a point source function(PSF) on CCD camera

Cause:
Diffraction of light, atmospheric turbulence, …

Example(Ground-based observation):
Quality of image is affected by turbulence
(light must pass through the atmosphere)



Example of
PFS

2.1 Atmospheric absorption and transmission

Atmosphere

- Protect us from harmful radiation
- **Not so friendly to the pursuit of astronomy**

Scattering

- Inversely proportional to λ^4
- Scattered sunlight is highly polarized
- **Disturb the radiation through turbulent**
  ⇒limits the ability of telescope(angular resolution)

Ground-based observation: visible wavelength range is limited

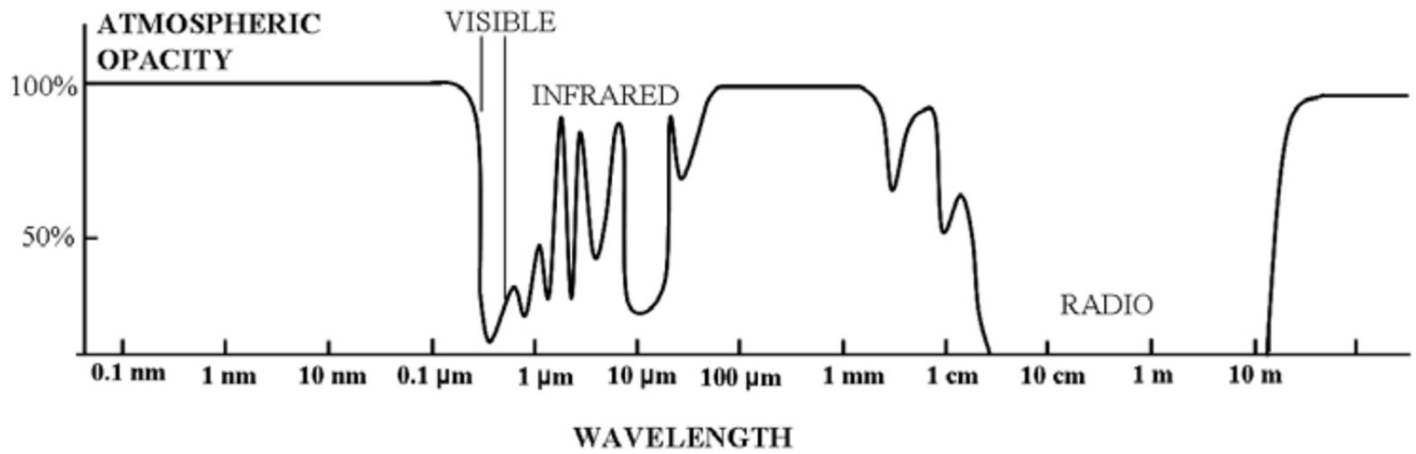
Visible

- Atmosphere absorbs in some very narrow bands (Oxygen: 760nm(A band), 688nm(B band))

UV, X-ray, Gamma-ray: Blocked by atmosphere

UV

- UV-A(320-400nm): Possible to be Observed well from highland
- UV-B&C(~320nm): Visible only >50km(with satellite, ballon or rocket)

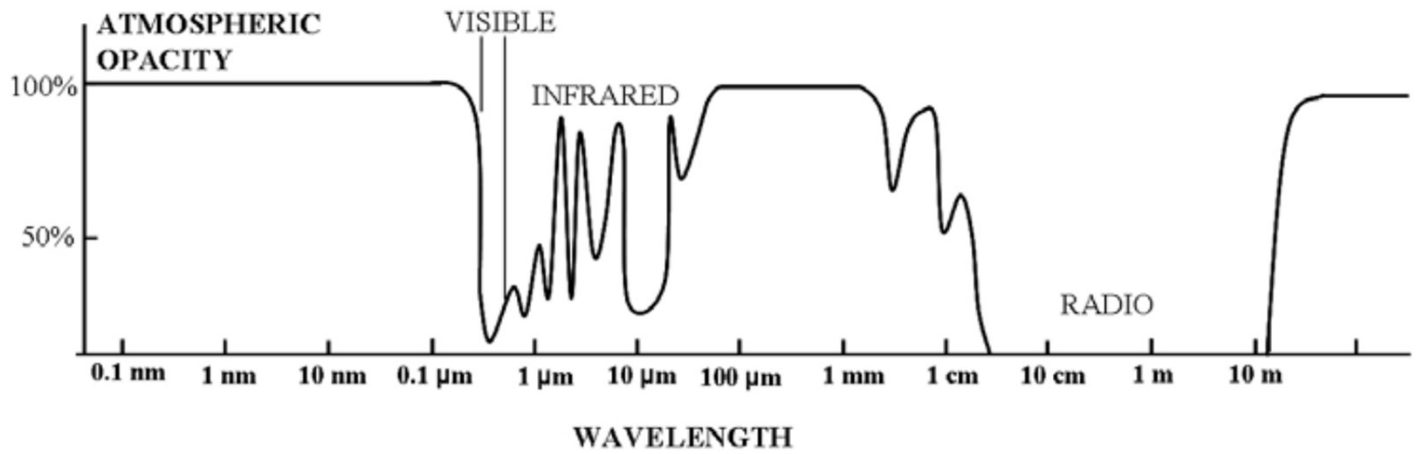


Infrared

- Atmosphere is opaque at some wavelength
  (Because of CO_2, H_2O)
- “$>20\mu$m” observation must be done from space or stratosphere

Radio

- Opaque in “$<$ 2cm” and “$>$ 20m” wavelength
- Possible to do good sub-mm observation from high, very dry sites



Observation Site

Observation from high-altitude sites:
Better to reduce the influence of absorption by atmosphere
(Example: Mauna Kea(Hawaii), desert of the Chilean Andes)

History:
Isaac Newton:
Proposed to do observation from highland (in "Opticks", 1730 treatise)

Charles Piazzi Smyth(1819-1900, Scotland):
Experimented with observing from high-altitude sites
(in Tenerife, Canary Islands)

Concentration of the atmosphere

- $N_2, O_2, Ar, CO_2, \cdots$

Ozone

- Occurs at high-altitude(10-30km)
- Affects UV transmission

Water Vapor

- Occurs at low-altitude, and varies with temperature, altitude

Precipitable water

- The amount of water along the line of sight
- Usually expressed in mm/km(path length) or total amount in airmass above the observatory

Atmospheric pressure (h<120km)

$$P(h) = P_0 e^{-h/H}$$

h: altitude
H: scale height (~8km)
P_0: standard atmospheric pressure (=101.325kPa)

Water vapor content: falls rapidly with height
(Most of water vapor is occurred from the sea)

Reference(precipitable water vapor):
ALMA site(altitude: 5.06km): about 1-2mm

Airmass (X)

Optical thickness of the atmosphere along line of sight

$$X = sec\, z = 1/cos\, z$$

z: zenith angle

(Treating the atmosphere as plane-parallel slabs)

Transform star's right ascension & declination(α , δ) into z:

$$cos\, z = sin\phi sin\delta + cos\phi cos\delta cos(LST - \alpha)$$

ϕ :latitude

LST: local sidereal time

True magnitude(m_λ)⇒Measured magnitude($m_\lambda(z)$)

$$m_\lambda(z) = m_\lambda + C_\lambda\, sec\, z\ (Bouguer's\ law)$$

C_λ: Extinction coefficient

(depends on temperature, site)

Photon arrival rate(S)

- **Transmission factor (atmosphere)** $T_{atmos}(\lambda)$

$$T = e^{-\mu_0(\lambda)L}$$

$\mu_0(\lambda)(cm^{-1})$: absorption coefficient at λ
L (cm) : path length for absorption

- **Additional transmission losses (telescope & instrument)**

$$S = \tau\eta S_0$$

τ : transmission factors
η : quantum efficiency of the detector
S_0: incident photon arrival rate

Direction of light

- **Star position on image is changed by refraction**
- **Deviation between image position & true one:**

$$\boldsymbol{\Delta z = (n-1) tan\, z}$$

n: refractive index

Example:

1. n=1.00029(700nm): $\Delta z \sim 59.8'' \tan z$
2. n=1.000295(480nm): $\Delta z \sim 60.8'' \tan z$

Conceivable trouble:
Light loss at the slit of a spectrometer (with narrow slit)

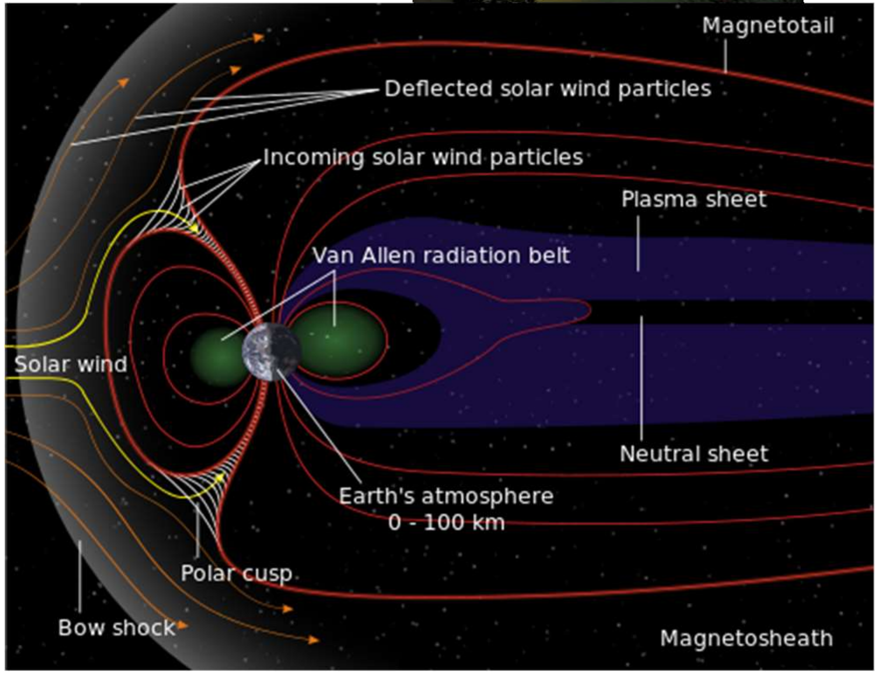
Solution:

- Calculate parallactic angle q
- Use ADC(atmospheric dispersion compensator)

2.2 Atmospheric emission, thermal and non-thermal

Aurora:
Atmosphere glowing phenomenon

- Non-thermal
- Observed only near the magnetic pole
- Caused by ionized particles in the solar wind
- Atomic oxygen⇒555.7nm emission
- Nitrogen⇒blue/purple emission



Airglow

- Non-thermal
- Contain OH lines, oxygen lines, near-IR continuum, …

OH lines

- Strongest lines in airglow
- Most of lines are belong to near-IR
- Excitation reaction: $\boldsymbol{H + O_3 \rightarrow OH^* + O_2}$
- Lines correspond to vibrational & rotational energy
- Radiated from ~90km altitude

OH spectrum

Taking images in broad spectral bands(or low-resolution):
OH lines will strengthen background
⇒**subtraction process will add noise**
⇒ **S/N ratio will be reduced**

high-resolution observation:
OH can be separated and
used for wavelength calibration

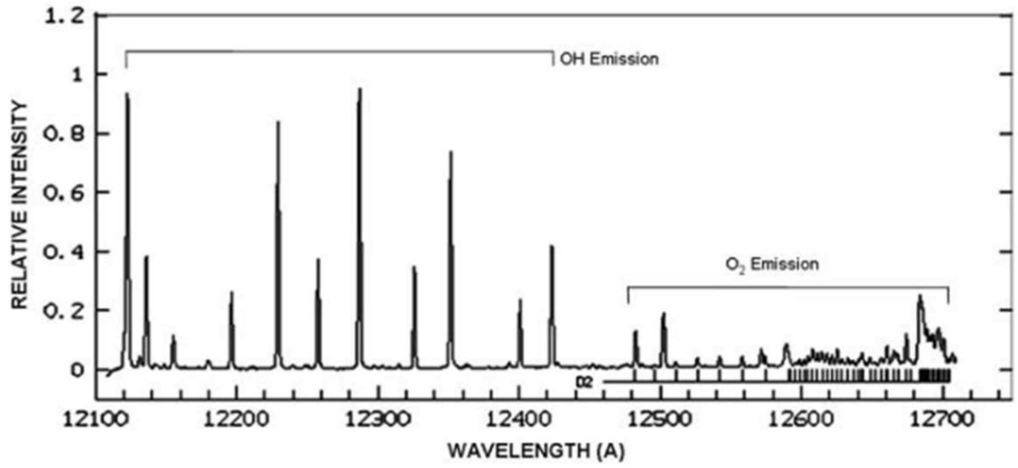
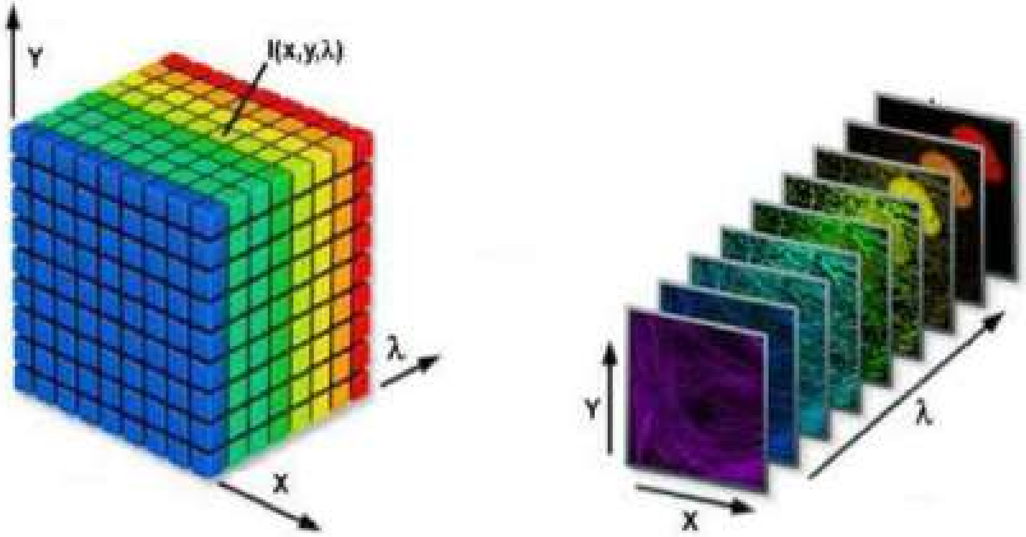


Figure 2.2. The presence of OH night-sky emission lines in part of the near-infrared window at 1.24 microns. Adapted from Oliva and Origlia (1992).

Data Cube



We can create data cube with images at thousands of successive wavelength (except images affected by OH lines)

Rayleighs(R):

Unit describing photon emission from a volume of atmosphere

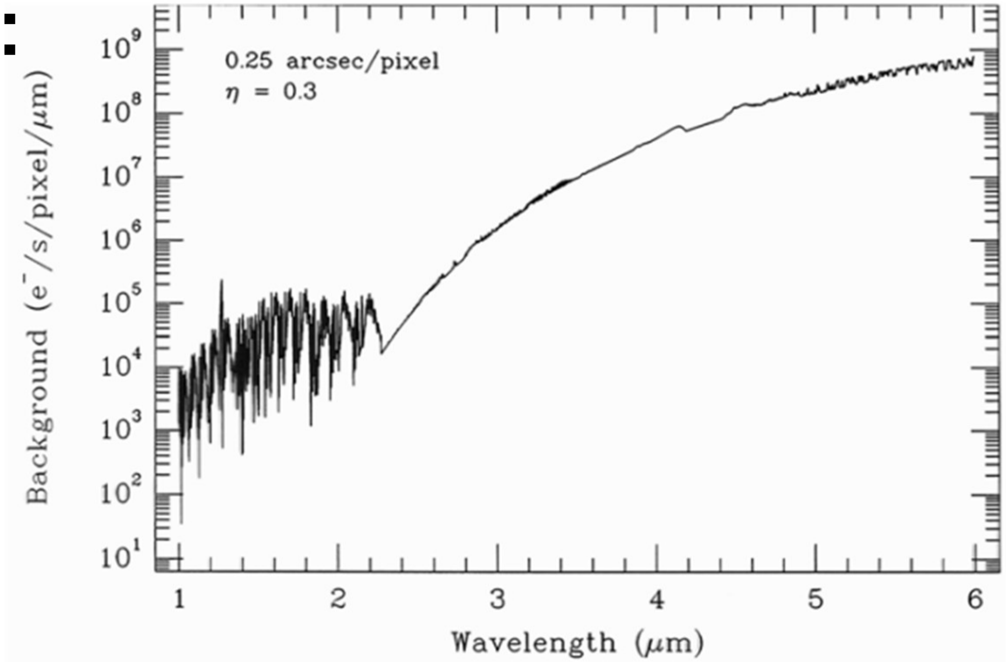
Thermal radiation by atmosphere

- Emissivity factor depends on atmospheric opaqueness (Strongest situation: semi-transparent)
- Water vapor: plays important role
- Follows Planck Function:

$$B_\lambda(T) = \frac{2hc^2\lambda^{-5}}{e^{hc/\lambda kT} - 1}$$

Photon flux per $arcsec^2$ (300K):

$$N_\lambda = \frac{1.41 \times 10^{16} \lambda^{-4}}{e^{48/\lambda} - 1}$$



Peak wavelength:
9.66μm(300K), 10.6μm(273K)

OH line vs continuum:
2.2μm or more: continuum brighter than OH line
11μm or more: continuum is dominant source

Mid/far-IR: observed from space/stratosphere

Other phenomena (relate with background)

- **Zodiacal light**
  - Scattered sunlight by tiny particles within the plane of the ecliptic
  - Magnitude: 22-23.5mag/$arcsec^2$

- **Moonlight**
  - Background magnitude difference (new/full Moon) 5(U band), 3.2(B), 1.8(V), 1(R), 0.7(I)

2.3 Turbulence

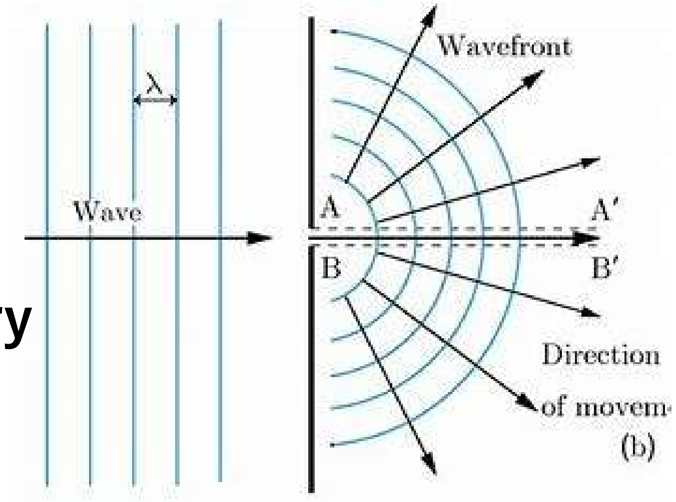
Turbulence:
Main impediment for observation

Measures:
Take point source image determined by the quality of telescope and diffraction of light

Diffraction

Plane wave passing through aperture:

- Creates a disturbance
- Interacts with the aperture breaks the symmetry
  ⇒spherical wavefronts



In a telescope:

Light wavefront is spherical
⇒blurred, complex image (due to interference effects)

General case:

Consider diffraction with Rayleigh-Sommerfeld (complex)
⇒Simplification (Fraunhofer diffraction, Fresnel diffraction)

Fraunhofer diffraction

- Condition: both light source and observer are far from the aperture (far field limit)
- Possible to be achieved with lenses or mirrors

Fresnel diffraction

- Condition: either light source or observer is far from the apreture

Airy disks (right figure):

- Interference pattern with circular aperture

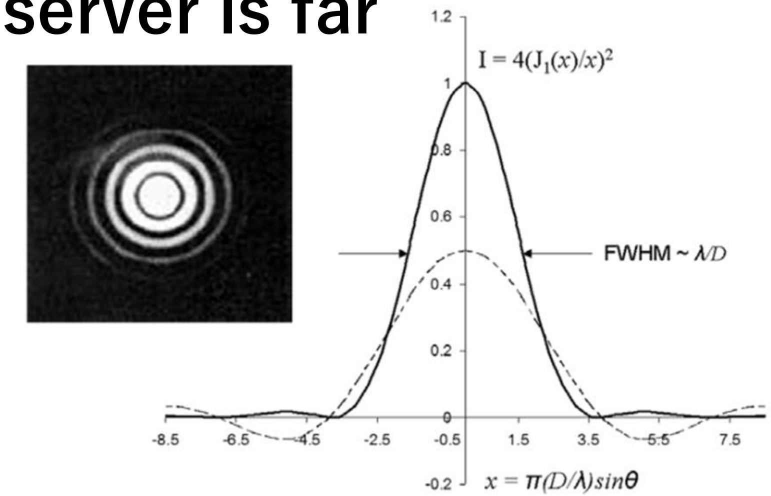


Figure 1.15. The point spread function (solid line) of the Airy diffraction pattern for a circular aperture of diameter D is illustrated both as an image and in cross-section.

Uncertainty principle $\Delta x \Delta p \sim h$ and diffraction/interference

Case: A plane wave(wavelength λ) pass through aperture (width D)

Plane wave:

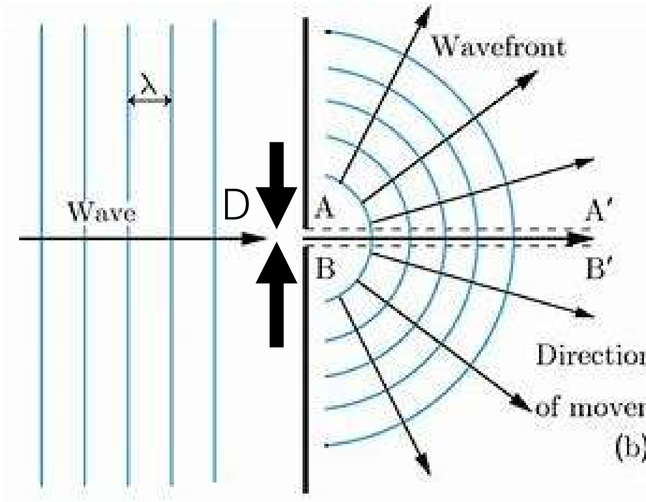
Photon's momentum $p=h/\lambda$

Uncertanity(momentum) $\Delta p=0$

⇒Uncertanity(position) $\Delta x=\infty$ (correspond to infinite wavefront)

Aperture:

$\Delta x=D$ ⇒ $\Delta p=h/D$



momentum is vector

⇒**direction of emergent wave: $\theta=\Delta p/p=\lambda/D$**

(diffraction limit)

Seeing

- Image is shifted by time-dependent turbulence
  ⇒**resulting in a fuzzy disk (seeing)**
- Caused by moving cells of air with different densities (←temperature variation)

Strehl ratio

- **Intensity ratio between observed peak & ideal peak** (diffraction limit)(typical value:0.01)
- High strehl ratio⇒**most of the light would be in central, and image sizes would be smaller**

Ultimate goal of adaptive optics(AO):

Making image smaller to achieve image quality

2.3.1 Kolmogorov theory and origin of seeing

Atmospheric impact on image quality

Light waves from distant sources: almost plane, but distorted by refraction & turbulence

Cause: variations in density, due to temperature variation
Example(refractive index n):

$$n-1=77.6\times10^{-6}(1+7.52\times10^{-3}\lambda^{-2})P/T$$

$$P=(P_0+\frac{4810P_{wv}}{T})$$

P:atmospheric pressure
T: temperature
P_0:normal atmospheric pressure
P_{wv}:pressure of water vapor

(550nm, 20°C, 101.325kPa, 50% humidity⇒n=1.000272663)

Effects of atmospheric turbulence:

Twinkling of starlight (Scintillation)

Incoming rays: refracted by patches of atmosphere with different index of refraction⇒path length should be changed

⇒**Intensity will vary randomly by interference**

Phase delay φ:

$$\varphi = \frac{2\pi}{\lambda} W$$

W: path length difference

How to reduce scintillation

Using telescope

Larger aperture has averaged out the interference effect

⇒**Scintillation will appear as blurred disk, seeing disk**

Cause of air turbulence

1. **Heat sources within the telescope**

   If the primary mirror is warmer than the air, local convection will occur and quality of image will be degraded

   (Ventilation is one of the measures to reduce the temperature difference)

2. **Wind around the telescope dome**

   Strong temperature gradient in troposphere
   ⇒wind shear will cause index of refraction fluctuation

Image quality and fluid dynamics

Predictions of turbulence requires a statistical model of mixing

Consider viscous fluid (characteristic length:L, average velosity:v_{av})

① $v_{av} < (critical\ value)$

Fluid motion is smooth & regular(laminar flow)

②$v_{av} > (critical\ value)$

Fluid becomes unstable and turbulent will occur

Reynord number($Re = v_{av}L/v$)

The parameter describes the balance between inertial and viscous force
(atmosphere: $Re \sim 10^6$)
When *Re* exceeds the critical value(Re>100), the flow transitions to chaotic

Structure function D(r)

One of the tools to consider turbulence statistically

Andrey Kolmogorov's formula:

$$\boldsymbol{D_n(r) = \langle |n(r_1) - n(r_2)|^2 \rangle = C_n^2 r^{2/3}}$$

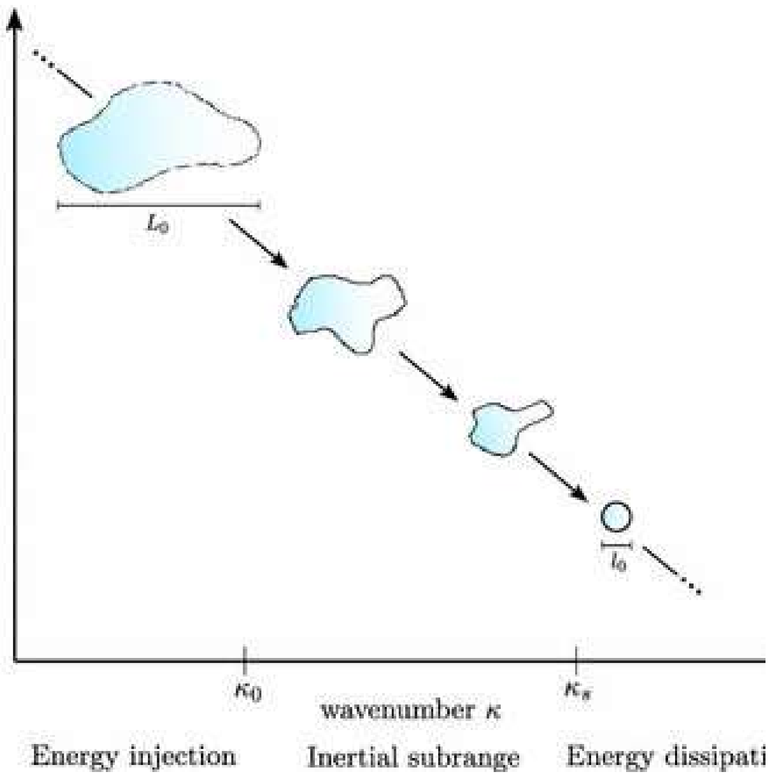
r_1, r_2: coordinates of points
$r = |r_1 - r_2|$
※〈X〉means the average of X

C_n^2: The factor of measure of the strength of turbulence depends on altitude, observation sites, and conditions
($10^{-14\sim-15}$ on the ground, 10^{-18} at 10km altitude)

Kolmogorov's idea for considering turbulence

Velocity fluctuations occurs on a wide range of space and time
⇒**form a turbulent cascade from larger to smaller scales**

1. **Energy enters at low spatial frequencies (large eddies, scale length L_0)**
2. **Energy is transported to smaller and smaller eddies**
3. **When Re reached ~1, kinetic energy of the flow is converted into heat (scale length will drop to l_0)**



Origin of seeing

Distribution of the size and number of eddies Φ(k):

- Fourier transform of the autocorrelation function B(r) (B(r)=$\langle f(r_1) f(r_1 + r)\rangle$, f :random variable(e.g. refractive index))
- If we substitute refractive index for random variable, Φ(k) expresses the power spectrum of the refractive index:

$$\boldsymbol{\Phi_n(k) = 0.033 C_n^2(h)|k|^{-11/3}} \qquad \frac{1}{l_0} \leq |k| \leq \frac{1}{L_0}$$

- **Origin of seeing: multitude of turbulent atmospheric cells acting like weak lenses**

- **Seeing size prediction: we have to recognize turbulence's effect of reducing the coherence of the beam**