M. Diffraction

1. General
Opaque body placed between light source and screen casts shadow of bright and dark regions; shadow is not geometrical shadow: "light deviates from rectilinear propagation — diffraction". Diffraction occurs in general whenever portion of wavefront is obstructed in some way.

a) Explanation in Huyghens—Fresnel picture:
every unobstructed point of wavefront, at a given time, serves as source of spherical secondary wavelets (of the same frequency as primary wave). Amplitude of optical field beyond obstruction is superposition of all these wavelets (considering their amplitudes and relative phases).

Diffraction pattern is wavelength dependent; idealized geometrical shadow corresponds to \( \lambda \to 0 \).

![Diagram]

\[ \Lambda_{\text{max}} = \overline{AP} - \overline{BP} \leq AB \]

Consider point sources A, B: if \( \lambda \gg \Lambda_{\text{max}} \) then \( \lambda \gg \overline{AB} \) and all wavelets interfere constructively in whole space beyond obstruction \( \Rightarrow \) large diffraction!

\( \lambda \ll \overline{AB} \), then space wave \( \lambda \gg \Lambda_{\text{max}} \) is limited to small region extending out directly in front of aperture and waves can only interfere there (constructively).
b) Explanation in photon picture and uncertainty principle:

1) Uncertainty affects in longitudinal (x) or transverse direction (y):

i) In propagation direction (x):
\[ \Delta p_x \cdot \Delta x = \hbar \]

Uncertainty of momentum \( p_x \):
\[ \hbar c \Delta v \cdot \Delta x = \hbar \]
due to finite length of wave train:
\[ \frac{\Delta v}{\Delta t} = \frac{\lambda}{c} \]

ii) Perpendicular to prop. direction:

\[ \Delta y = \frac{\Delta p_y}{p_x} \]

\[ \Delta p_y = p_x \Delta y \]
\[ = \frac{\hbar c}{\Delta t} \Delta y \]

Transversal localisation of photon produces uncertainty about transversal momentum:

\[ \Delta y \cdot \Delta p_y = \hbar \]
\[ \Delta \frac{\hbar v}{c} \cdot \Delta y = \hbar \]

\[ \Delta \frac{\hbar}{c} = \frac{\lambda}{\Delta y} \]
No real difference between interference and diffraction; it's customary to call

interference: superposition of a few waves

diffraction: large number of waves

two-beam interference simple: compare resulting phase shift of two beams to determine interference pattern

in diffraction: summing over infinite number of waves with continuous distribution of phase shifts \( \rightarrow \) integration needed to obtain pattern.

Helpful for diffraction: "phasors" (vectors representing wavelets; length of vector gives amplitude; direction gives phase angle). Superposition of light: vector addition of phasors.

Example:

\[ E_1 + E_2 = E_1 + E_2 \]

Constructive: \( \frac{E_1 + E_2}{E_1 + E_2} \)

\[ E_1 + E_2 \]

destructive
Two types of diffraction:
A) "Fresnel" diffraction: Source and/or observer at finite distance → curved wavefronts. Difficult

B) "Fraunhofer" diffraction: Source and observer at infinite distance → dealing with plane waves (easier)

or:

finite distances of source and screen but use of positive lenses to image them to infinity:

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2. Single Slit Diffraction

\[
sin \theta = \frac{\Delta_{13}}{a}
\]

- Spatial shift \( \Delta \) (or phase shift \( S = \frac{2\pi}{\lambda} \Delta \)) between waves from different parts of slit
- First order minima for \( \Delta_{12} = \pm \frac{\lambda}{2} \), \( \Delta_{13} = \pm \lambda \)

\[
S_{12} = \frac{\pi}{\lambda}
\]
\[
S_{13} = 2\pi
\]

In general: Minima for \[ a \sin \theta = \pm n \lambda \quad \text{or} \quad S = m \cdot 2\pi \]

Vector addition of elemental amplitude vectors \( \Delta A \) (phasors)

\[
\Delta A \rightarrow \rightarrow \rightarrow \rightarrow \rightarrow \rightarrow \rightarrow \rightarrow \rightarrow
\]
\[
A = \Sigma \Delta A
\]
\[
A \cdot \Sigma \Delta A
\]
a) zero-order maximum:

\[ A = \sum A_i \]

b) first-order minimum:

\[ \delta = 2\pi \text{ between outmost phasors} \]

\[ \text{addition of phasors results in} \]

\[ \text{full circle} \Rightarrow \text{resulting amplitude} \quad A = 0 \]

c) exactly in between (a) and (b):

\[ \delta = \frac{\pi}{2} \text{ between outmost phasors} \]

\[ \text{phasor addition: half circle, radius } \bar{R} \]

\[ \sum A_i = \frac{2\pi R}{2} = \frac{A_0}{2} \quad (A = 2\bar{R}) \]

\[ \Rightarrow A = \frac{2}{\pi} \sum A_i \]

d) first-order maximum:

\[ \text{phasor curve turns through } \frac{1}{2} \text{ revolutions of circle (radius } \bar{R}) \]

\[ \sum A_i = 3\pi R \quad \Rightarrow \quad A_0 = A \]

\[ \Rightarrow \quad A = \frac{2}{3\pi} \sum A_i \]
In general:

Resultant amplitude $A$ is the chord of the arc

$$\sin \frac{\delta}{2} = \frac{A/2}{r}$$

$$A = 2r \sin \frac{\delta}{2} = 2 \frac{\Sigma \Delta A_i \sin \frac{\delta_i}{2}}{r}$$

$$\delta = \frac{\Sigma \Delta A_i}{2} \quad \text{or} \quad r = \frac{\Sigma \Delta A_i}{\delta}$$

$$A = \frac{\Sigma A_i}{\delta} \frac{\sin \delta/2}{\delta/2} \quad \Rightarrow \quad A^2 \propto I = I_0 \left( \frac{\sin \delta/2}{\delta/2} \right)^2$$

first minimum at $\delta = 2\pi \Rightarrow \sin \delta = 0$.

place angle $\delta$ was related to angle of observation $\varphi$ by

$$\Delta = a \sin \varphi = \lambda \frac{\delta}{2\pi} \quad \Rightarrow \quad \delta = \frac{2\pi a}{\lambda} \sin \varphi$$

full expression for intensity profile of single-slit diffraction:

$$I = I_0 \left( \frac{\sin \left[ \frac{2\pi a}{\lambda} \sin \varphi \right]}{\frac{2\pi a}{\lambda} \sin \varphi} \right)^2$$

for small angles ($\sin \varphi \approx \varphi$)

$$I = I_0 \left( \frac{\sin \left[ \frac{2\pi a}{\lambda} \varphi \right]}{\frac{2\pi a}{\lambda} \varphi} \right)^2$$
\[ I = 0 \text{ (minima occur) at } \sin \theta = a \lambda; \]

angular width of main maximum: \[ \Delta \theta = \frac{2 \lambda}{a} \]

In Fraunhofer observation (screen at infinity or in focal plane of lens): single slit diffraction pattern is in its location independent of the position of the slit (slit at A and B produce same pattern).
Back to double-slit interference: two (infinitely thin) slits produced interference pattern with equidistant maxima at $\sin \delta = \frac{m \lambda}{d}$ and periodic intensity pattern

$$I(\delta) = 4I_0 \cos^2 \left( \frac{d \sin \delta}{\lambda} \right)$$

For double slit of distance $d$ and finite width $a$, the total interference-diffraction pattern is superposition of two-slit interference pattern (with maxima determined by distance $d$ of slits) with single slit diffraction pattern, produced by each of the individual slits (with maxima and minima determined by slit width $a$):

Full expression for double slit:

$$I(\delta) = 4I_0 \left[ \sin \left( \frac{2a \sin \delta}{\lambda} \right) \right]^2 \cos^2 \left( \frac{d \sin \delta}{\lambda} \right)$$

\hspace{1cm}

\hspace{1cm}

Single slit term \hspace{1cm} Double slit term

(minima at $\sin \delta = \frac{m \lambda}{a}$) \hspace{1cm} (maxima at $\sin \delta = \frac{\lambda}{d}$)
Diffraction at Circular Aperture

More important than slit geometry → most lasers, apertures, laser beams, have circular shape. Mathematically more difficult than slit (solved by Airy, 1801–1892).

Typical situation:
plane wave through circular aperture : pattern observed on distant screen : Fraunhofer diffraction pattern. Insert lens and screen (in focal distance) : same pattern. Lens into opening \( \Rightarrow \) no change! Image of distant point source by perfect aberration-free lens is never a point, but a diffraction pattern.

Principle of calculation: summation (integration) over all contributions from aperture with proper phase shift. Complete axial symmetry \( \Rightarrow \) solution independent of \( y \)

\( \Rightarrow \) circular symmetry.

Result:

\[
I(\theta) = I(0) \left[ \frac{2 \text{d} \Phi}{a \lambda} \left( \begin{array}{c} \frac{\sin \frac{\pi}{2} \sin 2 \theta}{\lambda} \end{array} \right) \right]^2 - I(0) \left[ \frac{2 \text{d} \Phi}{a \lambda} \frac{\sin \frac{\pi}{2}}{\lambda} \right]^2.
\]

\[
I_1 = \frac{1}{2 \pi} \int_0^{2\pi} \left( \begin{array}{c} \frac{\sin \frac{\pi}{2} \sin 2 \theta}{\lambda} \end{array} \right) \text{d} \phi
\]

\( J_1 \) = Bessel function; \( \delta \) = phase angle shift between aperture edges of 0.
Bessel function similar to amplitude function: oscillates between $+1$ and $-1$ values; however, period and amplitude not fixed:

$$u = \frac{2\pi}{\lambda} a \frac{a}{R}$$

$f_1(v) = 0$ when $u_1 = 3.83$

$$\frac{\varphi_1}{R} = \frac{3.83}{\lambda} = \frac{2\pi}{2a}$$

$$R = 1.22 \lambda$$

$$f_1(v_2) = 0 \quad \text{when} \quad u_2 = 7.02$$

$$\frac{\varphi_2}{R} = \frac{7.02}{\lambda} = \frac{2\pi}{\frac{2\pi}{2a}}$$

84% of intensity in Airy disk
91% within bands of second dark ring

Result: Intensity is function of circular symmetry: "Airy pattern" with strong high intensity circular spot ("Airy disk"), bordered by dark ring with

$$\sin \theta_1 = \frac{\varphi_1}{R} = 1.22 \frac{\lambda}{2a}$$

Second minimum:

$$\sin \theta_2 = 2.23 \frac{\lambda}{2a}$$

(not equal distance)

$q = \text{radius of Airy disk}$
For lens with circular aperture $da$, focused on screen:

$$\sin \theta = \frac{f}{f(\lambda)}$$

(radius of Airy disk)

$$\theta = 1.22 \frac{f \cdot \lambda}{2a(D)}$$

(size of diffraction disk)

Example: $f = 30 \text{ cm}$, $2a = 3 \text{ cm}$

Diffraction disk size $\theta = 12.2 \lambda$

Best lenses: $f \approx 2a$ ⇒ diff. spot is of dia. $\theta \approx \lambda$.

Limit for imaging process ⇒ Image point is of diameter (uncertainty) of approximately $\lambda$.

**Airy rings**

1.5 mm hole dia.

long exp.

0.5 mm dia of hole

**short exps.**

1 mm dia

(a)

(b)
Diffraction - limited size of image points important for resolution in imaging process of extended objects: resolution criterion ("Rayleigh criterion"): two points are resolved if center of one Airy disk falls on first minimum of neighboring Airy pattern:

\[
\sin \theta_{\text{min}} = 1.22 \frac{\lambda}{2a} \quad \text{and} \quad \Delta l_{\text{min}} = 1.22 \frac{\lambda f}{2a}
\]
Resolving power, defined by

\[
\frac{1}{\Delta s_{\text{min}}} \quad \text{or} \quad \frac{1}{\Delta l_{\text{min}}}
\]

\[\Delta l_{\text{min}} = 1.22 \frac{\lambda f}{2a}\]

Better resolution obtained by large lens diameter (Mt. Palomar Telescope \(2a = 5\) m \(\approx\) at 550 nm: angular resolution \(\approx 2.6 \times 10^{-2}\) arc seconds) or by viewing in UV light.

Diffraction limit of imaging process determines the density of light detectors (or grain size in photographic process) which is necessary: example, human eye: \(f = 20\) mm; pupil diameter (sunlight) \(2a = 2\) mm \(\Rightarrow\) \(\Delta l_{\text{min}} = 6700\) nm, about twice the spacing between light receptors on retina.

Should be able to resolve two points 1 in apart in 10 yard distance.

Diffraction limit (= uncertainty of linear momentum of light \(\pm\) to propagation) limits the parallelity of laser light: "perfectly parallel laser light is diffracted by its aperture so that \(\sin \delta \approx 1.22 \times 2a\). The smaller the diameter, \(2a\), of the laser beam, the larger the angular spread (experiment done in lab!). For transmission of lasers over large distances, \(\Rightarrow\) beam expanded first, then transmitted with less divergence.
For each shape of opening (or obstruction), a particular diffraction pattern results. Another example: rectangular aperture (still relating simple geometry). Diffraction pattern resembles single slit pattern appearing now along two crossed axes.
Dabney's Principle

Consider two complimentary plates — one negative, one positive (apertures ↔ obstacles).

Fraunhofer arrangement: light source $L$ produces amplitude pattern on screen $S$ which is $E_0 = 0$ everywhere aside of image point of light source. Being complimentary plates (CP) into beam and observe diffraction pattern $E(x, y)$ on screen:

(CP) Positive $\rightarrow$ amplitude distribution $E_1(x, y)$
(CP) Negative $\rightarrow$ $E_2(x, y)$

Each pattern $E_1(x, y)$ and $E_2(x, y)$ is obtained by integrating over the light coming through open areas bounded by apertures. Summing over the apertures of both screens $\rightarrow$ nothing opaque $\rightarrow$ diffraction pattern should be that of unobstructed wave: $E_1(x, y) + E_2(x, y) = E_0(x, y)$

But $E_0(x, y) = 0$ everywhere besides the image point of light ($x = y = 0$). Therefore everywhere else on the screen $E_1(x, y) + E_2(x, y) = 0$

Both amplitude patterns precisely equal in magnitude but opposite in sign (180° out of phase). Intensity patterns equal.
Diffraction by Multiple Slits / diffraction grating

\[ N \text{ long, parallel, narrow slits, \( \lambda \) smaller than wavelength} \]
\[ \text{centers-to-center separation} \]
\[ d \]
\[ \text{Intensity distribution:} \]
\[ I(\theta) = I_0 \left( \frac{\sin \beta}{\beta} \right)^2 \left( \frac{\sin N\lambda}{\sin \lambda} \right)^2 \]

- single-slit term due to interference effect (rapidly varying numerator, slowly varying denominator)

\[ \beta = \frac{2N \lambda \sin \frac{\theta}{2}}{\lambda} \]
\[ d = \frac{\pi d}{\lambda} \]

\[ I_0 \text{ is intensity in } \theta = 0 \text{ direction, emitted by any one of the slits; } I(\theta = 0) = N^2 I_0 \]

(intensity adds in \( \theta = 0 \) direction)
Each slit alone would generate exactly the same intensity distribution. Superimposed, the various contributions yield a multiple wave interference system modulated by single-slit diffraction envelope.

**Location of principal diffraction maxima:**

\[ I(\theta) \text{ is maximum if } \frac{\sin (Nd)}{\sin \theta} = N \]

\[ \Rightarrow \quad \theta = 0, \pm \frac{\pi}{N}, \pm \frac{2\pi}{N}, \ldots \pm \frac{m\pi}{N} \quad (m = 0, 1, \ldots) \]

or

\[ \theta = \frac{\pi}{N} L \sin \theta_{\text{max}} \quad \text{(this is equivalent with)} \]

\[ d \sin \theta_{\text{max}} = m\lambda \quad \Rightarrow \text{maxima at } \sin \theta_{\text{max}} = \frac{m\lambda}{d} \]

(same as for double slit; spacing of diffraction maxima is independent of \( N \))

**Location of principal diffraction minima:**

\[ I(\theta) \text{ is minimum if } \left( \frac{\sin (Nd)}{\sin \theta} \right)^2 = 0 \]

\[ \Rightarrow \quad \theta = \pm \frac{\pi}{N}, \pm \frac{2\pi}{N}, \ldots, \pm \frac{(N-1)\pi}{N}, \ldots \]

\[ \theta = \frac{\pi}{d \sin \theta_{\text{min}}} \]

\[ \sin \theta_{\text{min}} = \pm \frac{\lambda}{Nd}, \pm \frac{2\lambda}{Nd}, \pm \frac{(N-1)\lambda}{Nd}, \pm \frac{(N+1)\lambda}{Nd} \]
there will be \((N-1)\) minima between consecutive principal maxima; of course, between each pair of minima, there is a subsidiary maximum.

special cases:

a) double slit \(N=2\)

\[
\frac{\sin 2d}{\sin d} = 2 \cos d \quad \text{no} \quad I(\theta) = 4 \cos^2 \frac{2\theta}{d} \quad \text{diffraction term}
\]

see p. 252

b) \(N > 2\)

\(N-2\) subsidiary maxima and \(N-1\) subsidiary minima location of maxima stays the same but width (prop. to \(\frac{1}{N}\)) decreases and dark regions increase (subsidiary maxima are weak and hard to see)

c) \(N=6\) \(d=4a\)
for large number of slits, mostly visible are principal maxima (subsidiary maxima are very weak). Each principal maximum is bounded by two adjacent minima, if width of maximum is taken as distance between these adjacent minima, then angular width of maximum is \( \Delta \theta = \frac{2 \pi}{N} = \frac{\pi d \cos \phi}{\lambda} \)

\[ \Rightarrow \Delta \theta = \frac{2 \lambda}{Nd \cos \phi} \]

If \( N \) increases, spacing of maxima remains constant (\( \lambda/d \)) but width of maxima decreases. \( \Rightarrow \) multiple slit / grating can be used for color separation. Note that monochromatic light has width \( \frac{\lambda}{Nd \cos \phi} \) (This is termed instrumental broadening).

**Diffraction gratings**

repetitive array of diffusing elements (either apertures or obstacles) which result in periodic variations of phase, amplitude or both of incoming electromagnetic wave

\[ \Rightarrow \] diffraction effects similar to multiple slit diffraction which itself is called transmission amplitude grating
transmission amplitude relatively lossy; better arrangement: parallel notches ruled or scratched into surface of flat, clear glass plate. Each scratch is source of scattered light. Emerging wavefront periodically modulated in phase, not in amplitude: **phase grating**. Wavefronts vary in shape, equivalent to angular distribution of constituent plane waves. Other, very common type of grating: **reflection grating**; thin metallic film (usually aluminium) evaporated on flat glass blanks, grooves ruled into metal film. High light diffraction efficiency.

![Diagram of reflection grating](image)

![Diagram of phase grating](image)
Grating equation (for normal incidence):
\[ d \sin \theta_i = m \lambda \]

for reflection grating, the same equation as for transmission grating (emerging beams of transmission grating just flipped over to other side of grating in reflection). Values of \( m \) specify order of the various principal maxima. For light source with continuous spectrum, deflection angle of grating depends on \( \lambda \equiv \) spectral separation of light in all orders higher than 0. In zeroth order: no spectral separation; incoming light just reflected like from mirror.

Grating equation for general case of oblique incidence of light:
\[ d \left( \sin \theta_i - \sin \theta_c \right) = m \lambda \]

(due to path difference \( \Delta = \Delta_2 - \Delta_1 = d \left( \sin \theta_i - \sin \theta_c \right) \) between two adjacent beams)
disadvantage of these gratings: available light spread out over large number of spectral orders with low intensities (dilution of available intensity):Highest intensity is specularly reflected into zeroth order \((m=0)\) with \(\theta_m = \theta_i\); and is thus wasted.

Deficiency can be eliminated by ruling of grating with grooves of controlled shape ("blazed" grating):

Individual grooves of grating are inclined by "blaze angle" \(\gamma\) against the surface of the grating. Angular positions of 0th, 1st, 2nd... orders of grating are determined by \(d (\sin \theta_i - \sin \theta_m) = m \lambda\), where \(\theta_i\) and \(\theta_m\) are measured from normal of grating. Angular position of orders is not dependent on blaze angle, which therefore can be chosen.
independently! Maximum diffraction intensity will be diffracted into the direction of specular reflection, chosen by blaze angle. Blaze angle allows to concentrate most diffracted intensity into one particular order.

Example: in practice for normal incidence of light onto grating ($\delta_0 = 0$), zero order is weak (no specular reflection); most intensity diffracted into direction $2\gamma$:

\[ \delta_i - \delta_r = 2\gamma \quad \delta_i = 0 \]

\[ \Rightarrow \delta_r = -2\gamma \] (negative because incident and reflected rays on same side of normal)

this corresponds to particular non-zero order on one side of central image, when $\delta_m = -2\gamma$ i.e. $d \sin(-2\gamma) = m\lambda$ for the desired $\lambda$ and $m$.

**Grating spectroscopy**

Spectroscopy is separation of light into frequency or wavelength components. Diffraction grating extremely important
Periodic structure is of the order of $\lambda$.

Simplest grating arrangement in spectrometry like in prism spectrograph:

Deflection angle $\delta$ depends on $\lambda$ due to diffraction in case of grating (red components more diffracted than blue); in case of prism, deflection depends on refraction (blue components reflected more than red ones).

Major features of gratings in spectroscopy:

Instrumental broadening

Assume infinitesimally narrow incoherent source. Effective width of an emergent spectral line is defined as angular distance between zeros on either side of a principal maximum; this angular width $\Delta \phi$ is given by (p. 263)

$$\Delta \phi = \frac{2\lambda}{Nd \cos \delta}$$

and is due to instrumental broadening. Note that angular line width varies with width of grating, $Nd$. 

-270
To achieve narrowest possible line width, therefore, the whole grating needs to be illuminated by the light.

**Angular dispersion** \( D \)

- defined as difference in angular position, corresponding to a difference in wavelength:

\[
D = \frac{d\theta}{d\lambda}
\]

(defined in the same way as in case of prism see p. 11-14)

grating equation: \( \sin \theta = \frac{m\lambda}{d} \)

\[
\Rightarrow D = \frac{d\theta}{d\lambda} = \frac{m}{d \cos \theta}
\]

Angular dispersion increases with order, and is proportional to \( 1/d \).

**Chromatic resolving power** \( R \)

- quantity to characterize the least resolvable wavelength difference, or limit of resolution

- defined as \( R = \frac{\lambda}{\Delta \lambda} \) (like in prism case)

where \( \lambda \) is the mean wavelength between lines.
According to Rayleigh criterion, two adjacent wavelengths \( \lambda \) and \( \lambda + \Delta \lambda \) can be called resolved if maximum of \( \lambda \) falls into minimum of \( \lambda + \Delta \lambda \):

**Diffraction maximum:** \[ \sin \theta = \frac{m \lambda}{d} \]

**Diffraction minimum:** \[ \sin(\theta + \Delta \theta) = (m + \frac{1}{2}) \frac{\lambda}{d} \]

\[
\sin \theta + \Delta \theta \cos \theta = \frac{m \lambda}{d} + \frac{\lambda}{Nd} \\
\Delta \theta = \frac{\lambda}{Nd \cos \theta} = \frac{m \Delta \lambda}{d \cos \theta}
\]

\[
\frac{\lambda}{\Delta \lambda} = N \cdot m
\]

Angular dispersion from chromatic resolving power.

Resolving power depends on total number of grooves used by optical beam!

**Example:** Grating with 15,000 grooves (lines) per inch; width of grating 6 inches.

\[ N = 9 \times 10^4 \text{ lines} \]

Resolving power in 2nd order: \[ \frac{\lambda}{\Delta \lambda} = 1.8 \times 10^5 \]

At \( \lambda = 540 \text{ nm} \) grating could resolve \( \Delta \lambda = 0.003 \text{ nm} \).
Overlapping orders

grating equation: \[ d \sin \vartheta = m \lambda \]

For line of certain wavelength, \( \lambda \), in first order has precisely the same position \( \vartheta_m \) as half the wavelength in second order, or \( \lambda/3 \) of the wavelength in 3rd order.

If two wavelengths \( \lambda \) and \( \lambda + \Delta \lambda \) coincide in successive orders \( m \) and \( m+1 \), \( \Delta \lambda \) for which this is true, is called the free spectral range:

\[ d (\sin \vartheta_m - \sin \vartheta_{m+1}) = (m+1) \lambda = m (\lambda + \Delta \lambda) \]

\[ \Delta \lambda_{fsr} = \frac{\lambda}{m} \]

(same fsr as for Fabry-Perot Interferometer)
Diffraction from large number of identical objects

Multislit diffraction or grating diffraction is only one example of a more general problem: N identical small objects in "multi-arrangement" if objects distributed in random manner, N exactly overlapping and effectively non-interacting, Fraunhofer patterns, intensity in particular region is N times the individual object intensity diffused in that direction. Additionally, a bright spot exists at center of pattern whose flux density is N^2 times that of individual objects.

Diffraction pattern determined by form (slit width a, e.g.) of objects, resulting in form factor of pattern:

$$I(\theta) = N \cdot I_0 \left( \frac{\sin \frac{\pi a}{\lambda} \theta}{\frac{\pi a}{\lambda} \theta} \right)^2$$

Same effects arise from 2-dim. phase gratings.
Example: Diffraction of light by random droplets of water vapor (i.e., cloud particles) results in ring pattern around sun (corona). Diffraction rings red outside of ring, blue inside. Different from halo (refraction of light by ice particles: blue outside, red inside).

Regular 2-dim diffraction arrays:

Each scattering element behaves as coherent source; since regular periodicity of lattice of emitters, each emergent wave has fixed phase relation with respect to others. As a result, there will be certain directions in which constructive interference occurs. Also possible: 3-dim gratings.

Max von Laue used crystals as 3-dim gratings (1912), atom spacing several Å in crystals to use x-rays to see effe