Narrow Line Region

General Properties

Reminder: Narrow Line Region (Osterbrock, 1989, 1991):

- Line widths 200–700 km s^{-1}
- Allowed lines from H I, He I, He II
- Forbidden lines: strongest: [O III] $\lambda\lambda$4959, 5007, [N II] $\lambda\lambda$6548, 6583
- Studies for Sy 1 problematic as narrow and broad lines blend
- Gas diagnostics from [O III] $\lambda\lambda$ 5007/4959 and 4363 and [S II λ6716/λ6731 ratios: $T \sim 15000\,\mathrm{K}$ and $n_\mathrm{e} \sim 3 \times 10^3\,\mathrm{cm}^{-3}$, possible density gradient is observed
- NLR mass from Hβ emissivity and assuming spherical symmetry: $L_{\mathrm{H}\beta} = 2 \times 10^8\,L_\odot \Longrightarrow M \sim 7 \times 10^5 (10^4/N_\mathrm{e}) M_\odot$ and $R \sim 20 f^{-1/3} (10^4/N_\mathrm{e})^{2/3}\,\mathrm{pc}$, i.e., 90 pc with an estimated filling factor of $f = 10^{-2}$.

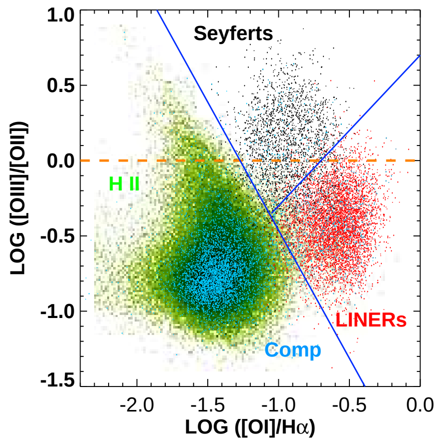
NLR Modeling

Models of the NLR aim to

- Determine flux of lines
- Reproduce line ratios and equivalent widths of narrow lines
- provide estimates for the line width

See talk by B. Groves at Xian AGN meeting for details:
`http://agn06.ihep.ac.cn/`

Nature of the NLR

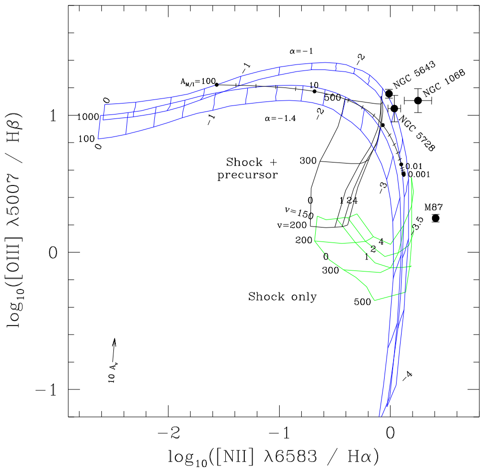


(Kewley et al., 2006)

Reminder: Line ratios are used to define the different types of Seyfert galaxies.

(Kewley et al., 2006; Baldwin, Phillips & Terlevich, 1981)

Nature of the NLR



(Allen et al., 1999, Fig. 1)

Photoionization models can reproduce ratios of strong observed lines such as [O III 5007]/Hβ ratio and absolute luminosity of these lines.

BUT: Strengths of high and low ionization stages cannot be reproduced simultaneously!

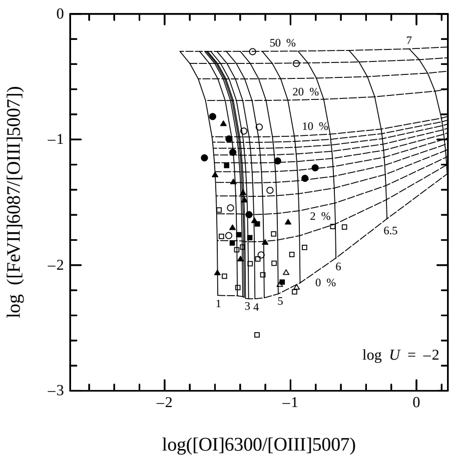
$\Longrightarrow$ rules out the simplest photoionization models!

Potential solution: shock ionization (Allen et al., 1999, and therein)!

Photons produced after a shock (where $T \sim 10^6$ K) can ionize pre-shock gas $\Longrightarrow$ combination of collisional ionization and photoionization.

Shock possibly related to jet/radio outflow.

Nature of the NLR



(Murayama & Taniguchi, 1998, Fig. 2)

Alternative explanation of unusual line ratios: two and multiple zone NLR models.

Triggered, e.g., by too strong Fe line emission

For example: High ionization nuclear emission region (HINER) models (Murayama & Taniguchi, 1998): 10% of NLR emission from high density ($n_e \sim 10^9\,\mathrm{cm}^{-3}$) photoionized region within torus which is responsible for emission from high ionized species.

Similar models have also been proposed, e.g, by Komossa & Schulz (1997) and by many other authors.

Problem: Too many free parameters $\Longrightarrow$ Search for physical constraints!

E.g., matter bounded vs. ionization bounded clouds, locally optimally emitting clouds,. . .

Imaging of the NLR

Line diagnostics: size of NLR: $\sim$90 pc or larger.

$\Longrightarrow$ for the nearest AGN imaging is possible

(e.g., Circinus galaxy: $d = 4$ Mpc $\longrightarrow 1'' = 19$ pc.

Imaging of NLR possible either using integral field spectroscopy or narrow-band filters.

Often used: narrow-band Hα and [O III] filters.

Results (see, e.g., Pogge 1988):

- ionization cones,
- stratified ionization structure in many AGN.

$\Longrightarrow$ Extended Narrow Line Region (ENLR).

In the following: two typical examples: NGC 1068 (=M77) and Circinus galaxy.

Similar studies have been performed for $\gtrsim$ 30 nearby AGN.

NGC 1068 (M77), NOAO 20″

NGC 1068, II

NGC 1068 (M77) (Bill Arnett)

NGC 1068 (M77): Seyfert 2 nucleus at $z = 0.003$ ($d \sim 15$ Mpc), one of the best studied galaxies in the sky.

Circinus galaxy:

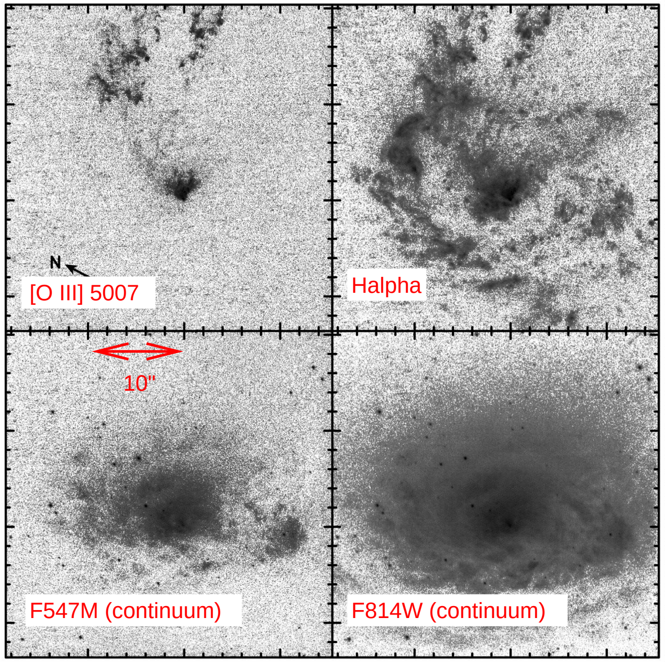
- $d \sim 4$ Mpc ($1'' \sim 19$ pc)
- 2nd nearest AGN on southern hemisphere after Cen A
- SAb galaxy
- Seyfert 2 nucleus

NGC 1068, III

NGC 1068 (M77) core with HST in O III

NGC 1068 (M77): Seyfert 2 nucleus at $z = 0.003$ ($d \sim 15$ Mpc), one of the best studied galaxies in the sky.

Pogge (1988): Extended ionizing radiation cone from the nucleus of NGC 1068, along the direction of the radio jet.



(HST Wilson et al., 2000, Fig. 2)

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Jets and Radio Loud AGN

Synchrotron Radiation

Jets are observed to have strong polarization and power law radio spectrum. These are characteristics of synchrotron radiation.

> Synchrotron-Radiation (=Magnetobremsstrahlung): Radiation emitted by relativistic electrons in a magnetic field.

Goal: Qualitative analysis:

1. Derive the motion of electrons in magnetic fields
2. Then use Larmor's formula to obtain the radiation characteristic from relativistic motion
3. Use the Doppler-effect to convert into the observer's frame of reference.
4. Integrate over electron distribution to obtain the final spectrum.

Detailed theory: see Ginzburg & Syrovatskii (1965), Ginzburg & Syrovatskii (1969), Blumenthal & Gould (1970), Reynolds (1982).

Relativistic Motion

Lorentz-Force ($\boldsymbol{E} = 0$)

$$\frac{d\boldsymbol{p}}{dt} = \frac{e}{c}\boldsymbol{v} \times \boldsymbol{B} \quad \text{where} \quad \boldsymbol{p} = \frac{m_e \boldsymbol{v}}{\sqrt{1-\beta^2}} = \gamma m_e \boldsymbol{v} \tag{10.1}$$

where $\beta = v/c$.

Assumption: No radiative losses (i.e., electron does *not* emit synchrotron radiation...): $\gamma = \text{const}$.

Velocity-vector of the electron:

$$\boldsymbol{v}_\parallel = \frac{\boldsymbol{v}\cdot\boldsymbol{B}}{B}\frac{\boldsymbol{B}}{B} \qquad \boldsymbol{v}_\perp = \frac{\boldsymbol{B}\times(\boldsymbol{v}\times\boldsymbol{B})}{B^2} \tag{10.2}$$

$$|\boldsymbol{v}_\parallel| = v\cos\alpha \qquad |\boldsymbol{v}_\perp| = v\sin\alpha \tag{10.3}$$

where α (pitch-angle): $\angle(\boldsymbol{v}, \boldsymbol{B})$

No acceleration parallel to the $\boldsymbol{B}$-field $\Longrightarrow$ only $v_\perp$ is interesting $\Longrightarrow$ circular motion:

$$m_e a_\perp = \frac{\gamma m_e v_\perp^2}{R} = \frac{e}{c} v_\perp B \tag{10.4}$$

$$\frac{v_\perp}{R} = \frac{eB}{\gamma m_e c} = \frac{\omega_L}{\gamma} = \omega_B \tag{10.5}$$

where $\omega_L = 2\pi\nu_L$: Larmor frequency (also Cyclotron frequency, gyrofrequency).

Numerical values

Numerically, Larmor frequency is

$$\nu_L = 2.8 B_{1\,G}\,\text{MHz} \tag{10.6}$$

The radius of the orbit (Larmor radius) is

$$R = \frac{\gamma v_\perp}{\omega_L} \approx 10^7 \frac{E_{1\text{GeV}}}{B_{1\,G}}\,\text{cm} \tag{10.7}$$

Typical values:

$B \approx 10^{-5}\,\text{G}$, $E = 1\,\text{GeV}$, $\Longrightarrow R = 3 \times 10^{13}\,\text{cm}$ (2 AU).

i.e., small on cosmic scales

Radiated Energy, I

Electrodynamics: Radiation of an accelerated electron:

$$P_{em} = \frac{2e^2}{3c^3}\gamma^4\left(a_\perp^2 + \gamma^2 a_\parallel^2\right) \tag{10.8}$$

where a is the acceleration.

([Messy] derivation by Lorentz-transforming the classical Larmor formula ($P = (2e^2/3c^3) \cdot a^3$), see, e.g., Shu)

For circular motion, $a_\perp = \omega_B v_\perp$ and $a_\parallel = 0$. Hence

$$P_{em} = \frac{2e^2}{3c^3}\gamma^4 \frac{v_\perp^2 e^2 B^2}{\gamma^2 m_e^2 c^2} \tag{10.9}$$

$$= 2\beta^2\gamma^2 c \cdot \sigma_T \cdot U_B \cdot \sin^2\alpha \tag{10.10}$$

where $U_B = B^2/8\pi$ (Energy density of the B-field), $\sigma_T = \frac{8\pi e^4}{3m_e^2c^4}$ (Thomson-cross section).

Presence of σ_T due to quantum electrodynamics: Derivation of synchrotron-radiation in frame of reference of electron via interaction of electron with a virtual photon of the magnetic field (i.e., Compton scattering with virtual photon).

Radiated Energy, II

Total energy radiated: Integration over all electrons.

Assumption: Isotropic velocity distribution.

Average pitch angle

$$\left\langle \sin^2\alpha \right\rangle = \frac{1}{4\pi}\int_0^{4\pi} \sin^2\alpha\, d\Omega = \frac{1}{4\pi}\int_0^{2\pi} d\varphi \int_0^{\pi} \sin^2\alpha \sin\alpha\, d\alpha = \frac{2}{3} \tag{10.11}$$

therefore

$$\langle P_{em}\rangle = \frac{4}{3}\beta^2\gamma^2 c\sigma_T U_B \tag{10.12}$$

for $\beta \longrightarrow 1$.

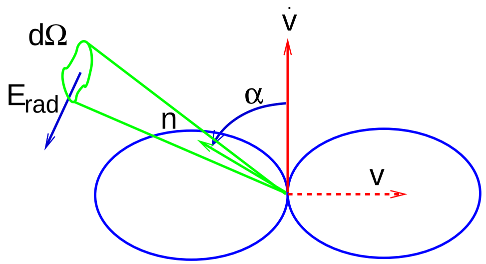
Note: Since $E = \gamma m_e c^2 \Longrightarrow P \propto E^2 U_B$.

Note: $P_{em} \propto \sigma_T \propto m_e^{-2} \Longrightarrow$ Synchrotron radiation from charged particles with larger mass (protons,...) is negligible.

Note: Life-time of particle of energy E is

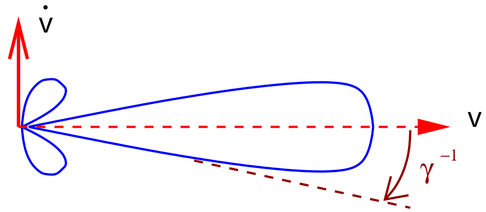
$$t_{1/2} \sim \frac{E}{P} \propto 1/(B^2E) = 5\,\text{s}\left(\frac{B}{1\,\text{T}}\right)^{-2}\gamma^{-1} = 1.6 \times 10^7\,\text{years}\left(\frac{B}{10^{-7}\,\text{T}}\right)^{-2}\gamma^{-1} \tag{10.13}$$

Single Electron spectrum, I



after Rybicki & Lightman, Fig. 3.5

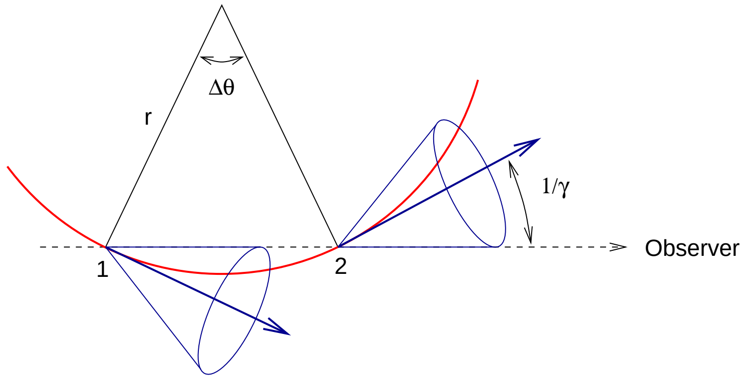
Frame of reference of electron: Emitted radiation has dipole characteristic (see, e.g., Eq. 6.2).



after Rybicki & Lightman, Fig. 4.11d

Lorentz-Transform into laboratory system: Forward Beaming. Opening angle is $\Delta\theta \approx \gamma^{-1}$.

Single Electron spectrum, II

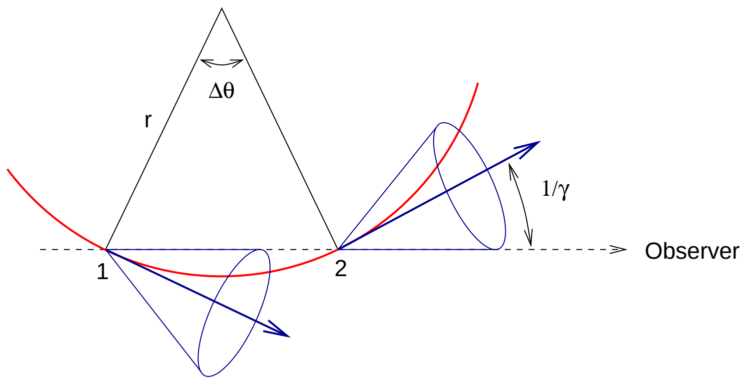


(Rybicki & Lightman, 1979, after Fig. 6.2)

Electron frame of rest: beam passes observer during time

$$\Delta t = \frac{\Delta\theta}{\omega_\mathrm{B}} = \frac{m_\mathrm{e}c\gamma}{eB}\frac{2}{\gamma} = \frac{2}{\omega_\mathrm{L}} \tag{10.14}$$

Single Electron spectrum, III



(Rybicki & Lightman, 1979, after Fig. 6.2)

Observer frame: Doppler! (electron is closer at end of beam)
$\Longrightarrow$ observed pulse duration:

$$\tau = \left(1 - \frac{v}{c}\right)\Delta t = (1-\beta)\Delta t \tag{10.15}$$

Single Electron spectrum, IV

For $\gamma \gg 1$, i.e., $\beta = v/c \sim 1$

$$\frac{1}{\gamma^2} = 1 - \frac{v^2}{c^2} = (1+\beta)(1-\beta) \approx 2(1-\beta) \tag{10.16}$$

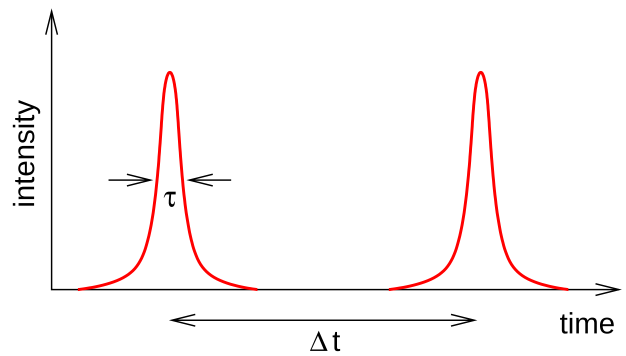
such that

$$\tau = (1-\beta)\Delta t = \frac{1}{2}\left(1 - \frac{v^2}{c^2}\right)\Delta t = \frac{1}{\gamma^2\omega_\mathrm{L}} \tag{10.17}$$

Thus the characteristic frequency of the radiation is given by

$$\omega_\mathrm{c} = \gamma^2\omega_\mathrm{L} = \frac{eB}{m_\mathrm{e}c}\left(\frac{E}{m_\mathrm{e}c^2}\right)^2 \tag{10.18}$$

Resulting Field



after Shu, Fig. 18.2

The observed time-dependent E-Field, $E(t)$, from one electron is a sequence of pulses of width τ, separated in time by Δt.

To a good precision, we can approximate these single peaks with δ-functions.

In reality: derive spectrum by Fourier-transforming $E(t)$. Basic result is the same.

Nonthermal Synchrotron Radiation, I

Spectral energy distribution P_ν of one electron with total energy $E = \gamma m_e c^2$ is

$$P_\nu(\gamma) = \frac{4}{3}\beta^2\gamma^2 c\sigma_T U_B \delta(\nu - \gamma^2\nu_L) \quad (10.19)$$

where $\delta(x)$ is a δ-function, i.e.,

$$\delta(x) = 0 \quad \text{for } x \neq 0 \quad \text{and} \quad \int_{-\infty}^{+\infty} \delta(x)\,dx = 1 \quad (10.20)$$

i.e., electron with energy γmc^2 "blinks" at frequency $\nu = \gamma^2\nu_L = 1/\tau$.

For an electron distribution, $n(\gamma)$, the emitted spectrum is found by properly weighting contributions of electrons with different energies:

$$P_\nu = \int_1^\infty P_\nu(\gamma) n(\gamma) d\gamma \quad (10.21)$$

Most important case: nonthermal synchrotron radiation, where electrons have a power-law distribution

$$n(\gamma)d\gamma = n_0\gamma^{-p}d\gamma \quad (10.22)$$

Nonthermal Synchrotron Radiation, II

Insert distribution into Eq. (10.21) and perform the integration:

$$P_\nu = \int_1^\infty \frac{4}{3}\beta^2\gamma^2 c\sigma_T U_B \delta(\nu - \gamma^2\nu_L) n_0 \gamma^{-p} d\gamma \quad (10.23)$$

since $\gamma \gg 1$: $\beta \approx 1$

$$= A \int_1^\infty \gamma^{2-p}\delta(\nu - \gamma^2\nu_L) d\gamma \quad (10.24)$$

substituting $\nu' = \gamma^2\nu_L$, i.e., $d\nu' = \nu_L 2\gamma d\gamma$

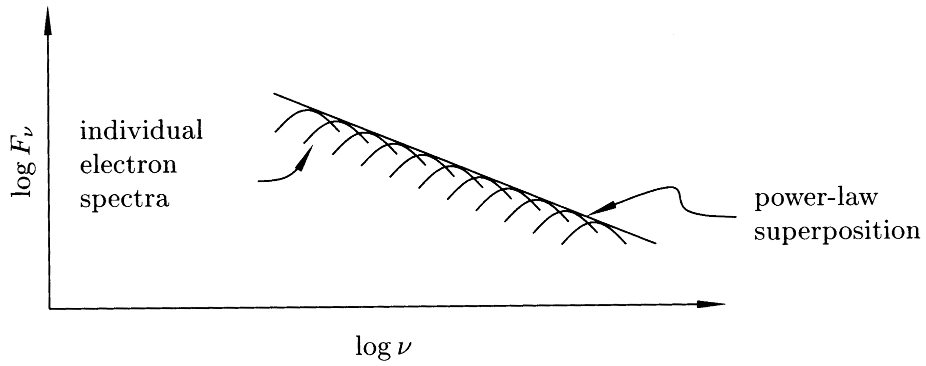
$$= B \int_{\nu_L}^\infty \gamma^{1-p}\delta(\nu - \nu')d\nu' \quad (10.25)$$

since $\gamma = (\nu'/\nu_L)^{1/2}$, one finally finds

$$P_\nu = \frac{2}{3} c\sigma_T n_0 \frac{U_B}{\nu_L}\left(\frac{\nu}{\nu_L}\right)^{-\frac{p-1}{2}} \quad (10.26)$$

The spectrum of an electron power-law distribution is a power-law!

Nonthermal Synchrotron Radiation, III



Shu, Fig. 18.4

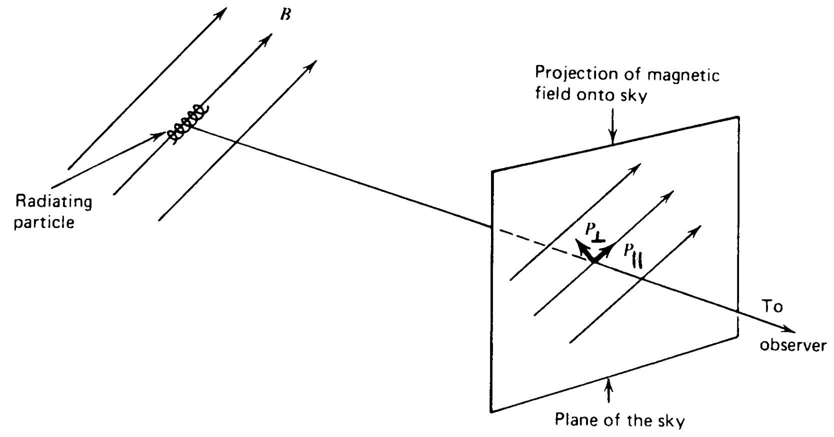
Summary

What we have done so far:

1. Motion of the electron
2. Radiation characteristic from relativistic motion
3. Doppler-effect
4. Integration over electron distribution

It is possible to do the same analytically without any approximations. This is too complicated to be done here. See the references for details.

Exact Results, I



(Rybicki & Lightman, 1979, Fig. 6.7)

Exact calculation needs to take into account polarization of synchrotron radiation.

$F(x) = x\int_x^\infty K_{5/3}(\eta)d\eta$ and $G(x) = xK_{2/3}(x)$

x	$F(x)$	$G(x)$	x	$F(x)$	$G(x)$
0	0	0	0.90	0.694	0.521
0.001	0.213	0.107	1.0	0.655	0.494
0.005	0.358	0.184	1.2	0.566	0.439
0.01	0.445	0.231	1.4	0.486	0.386
0.025	0.583	0.312	1.6	0.414	0.336
0.050	0.702	0.388	1.8	0.354	0.290
0.075	0.772	0.438	2.0	0.301	0.250
0.10	0.818	0.475	2.5	0.200	0.168
0.15	0.874	0.527	3.0	0.130	0.111
0.20	0.904	0.560	3.5	0.0845	0.0726
0.25	0.917	0.582	4.0	0.0541	0.0470
0.29	0.918	0.592	4.5	0.0339	0.0298
0.30	0.918	0.596	5.0	0.0214	0.0192
0.40	0.901	0.607	6.0	0.0085	0.0077
0.50	0.872	0.603	7.0	0.0033	0.0031
0.60	0.832	0.590	8.0	0.0013	0.0012
0.70	0.788	0.570	9.0	0.00050	0.00047
0.80	0.742	0.547	10.0	0.00019	0.00018

Exact Results, II

Result of exact calculation for both polarization directions:

$$\begin{pmatrix} P_\parallel \\ P_\perp \end{pmatrix} = \frac{\sqrt{3}}{2}\frac{e^3 B}{mc^2}\begin{pmatrix} F(\nu/\nu_c) - G(\nu/\nu_c) \\ F(\nu/\nu_c) + G(\nu/\nu_c) \end{pmatrix} \quad (10.27)$$

where

$$F(x) = x\int_x^\infty K_{5/3}(y)dy \quad (10.28)$$

$$G(x) = xK_{2/3}(x) \quad (10.29)$$

and K_i are modified Bessel-functions of i-th order

Polarization allows to measure the magnetic field direction

Total Emitted Spectrum

The total emitted power for monoenergetic electrons is

$$P(\nu) = P_\parallel(\nu) + P_\perp(\nu) \propto F(\nu) \quad (10.30)$$

As before, the total emitted spectrum is found by integrating over the electron energy distribution. For a power-law:

$$\begin{pmatrix} P_\parallel(\nu) \\ P_\perp(\nu) \end{pmatrix} = \left(\frac{\sqrt{3}}{2}\right) n_0 \frac{e^3 B}{m_e c^2}\begin{pmatrix} J_F - J_G \\ J_F + J_G \end{pmatrix}\left(\frac{2\nu}{3\nu_L}\right)^{-(p-1)/2} \quad (10.31)$$

where

$$J_F = \frac{2^{(p+1)/2}}{p+1}\Gamma\left(\frac{p}{4}+\frac{19}{12}\right)\Gamma\left(\frac{p}{4}-\frac{19}{12}\right) \quad (10.32)$$

$$J_G = 2^{(p-3)/2}\Gamma\left(\frac{p}{4}+\frac{7}{12}\right)\Gamma\left(\frac{p}{4}-\frac{1}{12}\right) \quad (10.33)$$