Outflows & Jets: Theory & Observations
Lecture plan & schedule

Summer term 2011
Henrik Beuther & Christian Fendt

15.04  Today: Introduction & Overview ("H.B." & C.F.)
29.04  Definitions, parameters, basic observations (H.B.)
06.05  Basic theoretical concepts & models; MHD (C.F.)
13.05  MHD & plasma physics; applications (C.F.)
20.05  Radiation processes (H.B.)
27.05  Observational properties of accretion disks (H.B.)
03.06  Accretion disk theory and jet launching (C.F.)
10.06  Theory of interactions: entrainment, Instabilities, shocks (C.F.)
17.06  Outflow-disk connection, outflow entrainment (H.B.)
24.06  Outflow-ISM interaction, outflow chemistry (H.B.)
01.07  Outflows from massive star-forming regions (H.B.)
08.07  Extragalactic jets: observations, radiation mechanisms (C.F.)
15.07  Some aspects of relativistic jet theory (C.F.)
Outflows & Jets: Theory & Observations

Extragalactic jets – discoveries

M87 (Vir A, NGC 4486)
-> first jet source detected

Discovered 1918 by Curtis:
"A curious straight ray lies in a gap in the nebulosity ... apparently connected with the nucleus by a thin line of matter. The ray is brightest at its inner end ..."

Un-noticed until mid-1950s ...
Baade & Minkowski (1954): M87 is optical counterpart of strong radio source:
"The interpretation ... is that the jet was formed by ejection from the nucleus and that the [OII] line is emitted by .... the material which forms the jet ...."

M87: Baade 1954: λλ 3500-5000; λλ < 4500
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Extragalactic jets – discoveries

M87 - First jet source detected

Baade (1956):

- optical polarisation in M87
- resolving the jet; 3 inner condensations
- polarization degree ~30%
- interpretation: synchrotron radiation
  (note contemporary discovery of Crab pulsar & theory of radio emission, Shklovskii 1953)
- very first hint on the magnetic character of astrophysical jet phenomenon

Hiltner (1959):

- polarization vector maps of M87 jet:

  "no significant polarization was observed in M87 except in the jet"
The central engine:
High (relativistic) jet speed
  -> jet launched close to BH

M87 high resolution 43GHz observations (1000 AU resolution)
  - initial opening angle ~ 60°
  - strong collimation at ~30-100 $R_S$
    (Schwarzschild radii) from BH
  - collimation continues out to ~ 1000 $R_S$

-> model of jet formation:
"jets are formed by an accretion disk around the central black hole, threaded by a magnetic field"

M87 central region (Biretta et al, 1999)
Extragalactic jets – resolution

Centaurus A Radio Source
Australian VLBI Network

D = 3.4 Mpc; 1 mas = 0.02 pc

VLBI, 6.6 GHz
20 mas

ATCA, 8.6 GHz
30"

VLA, 4.9 GHz
4'

Parkes, 5.0 GHz
2"

ATCA, 1.3 GHz
5'
Nomenclature

of radio double sources:

- **core**: central source, active nucleus (supermassive BH + disk)
- **jet**: relativistic, hot, magnetized plasma knotty structure
- **counter jet**: less prominent, often (partly) invisible
- **hot spots**: terminal shock of jet, jet plasma thermalised
- **cocoon**: layer of back-flowing material surrounding the jet
- **lobes**: bow-like clouds of hot, shocked gas

max resolution: 0.00015 ''
~ 0.1pc = 130 lightdays
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Extragalactic jets – jet polarization

Example: M87 HST & VLA observations:

(Perlman et al 1999)

- optical / radio polarisation
- resolution 0.2 (15 pc)
- P up to 40 – 50%
  ~ maximum for optically-thin synchrotron emission
- highly ordered magnetic field
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Extragalactic jets – X-ray observations

Chandra X-ray survey of radio selected jet sources (Marshall, Schwartz et al):

M87

- X-ray issynchrotron
- X-ray source is jet, not disk
- inner knots brighter

http://chandra.harvard.edu/photo/2001/0134/
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Extragalactic jets – X-ray observations

**Chandra X-ray survey** of radio selected jet sources (Marshall, Schwartz et al): 54 sources / 40 observed / 25 detected in X-ray

-> allows to estimate **magnetic field** B & **Doppler factor** $\delta$

(using minimum energy assumption & rel. beaming to get IC/CMB X-rays)
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Extragalactic jets – X-ray observations

**Gamma-rays** from M87 (H.E.S.S. telescope):

![Gamma-ray image from M87](image)

Left: **gamma-ray intensity** in M87, statistical significance of gamma-ray signal ~ 13 standard deviations.
Black contours indicate **radio image** (Owen et al. 2000). Extent of gamma-ray signal ~ 0.1 degr compatible with H.E.S.S. point spread function
- indicating gamma rays from a source **pointlike** for H.E.S.S
- upper limit for the **source size** ~ 14 kpc

Right: superimposed on radio, cross indicates centroid of gamma-ray signal
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Extragalactic jets – jet origin

Resent efforts to resolve jet base in M87 (Kirchbaum et al. 2007)

- transverse size of jet base: \(195 \times 54 \mu\text{as} = 21 \times 6 \text{ light days} = 69 \times 19 R_S\)
- transverse size of jet at \(D = 0.5 \text{ mas}\): \(174 R_S\)

![GMVA 86 GHz, April 2004](image)
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Extragalactic jets – central engine

Central engine:
example **NGC 4258**:
Water maser spectroscopy, polarimetry

Central radio jet perp. to central molecular disk (Cecil et al. 2000)

Molecular disk models
-> magnetic field:
  (e.g. Modjaz et al. 2005):
  -> $B_{\text{tor}} \sim 90-300 \text{ mG at 0.2pc}$
  -> $B_{\text{rad}} \sim 30 \text{ mG at 0.15pc}$
  -> $dM/dt \sim 10^{-3.7} \text{ M}_\odot/\text{yr}$
Evidence for a BH in jet source NGC 4258 (Miyoshi et al 1995)

- Keplerian disk rotation
- central mass: $3.6 \times 10^7 \, M_\odot$

(unique example, besides center of Milky Way)
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Extragalactic jets – spectral energy distribution

AGN / blazar spectra

- two peaks (FIR, MeV)
- break in radio, dip in UV/X-ray, cut-off for TeV (?)
- variability in flux, constant slope

spectral index $\alpha \rightarrow S(\nu) \sim \nu^{-\alpha}$
  
core: $\alpha \sim 0$ (flat), jets: $\alpha \sim 0.6$ (steep)
  hot spots: $\alpha \sim 0.5...1.0$

![3C 279 Spectral Energy Distribution](image)

SEDs of NGC 6251, Cen A & M 87, compared to blazar sequence (Ghisellini et al. 2005)
Extragalactic jets – spectral energy distribution

AGN / blazar spectra
- two peaks (FIR, MeV)
- break in radio, dip in UV/X-ray, cut-off for TeV (?)
- variability in flux, constant slope
- spectral index $\alpha$
  $\Rightarrow S(\nu) \sim \nu^{-\alpha}$
  core: $\alpha \sim 0$ (flat), jets: $\alpha \sim 0.6$ (steep)
  hot spots: $\alpha \sim 0.5...1.0$

SEDs of blazars, compared to injection tow models: steady-state, finite time (Ghisellini et al. 2002)
Extragalactic jets – spectral energy distribution

AGN / blazar spectra

- two peaks (FIR, MeV)
- break in radio, dip in UV/X-ray, cut-off for TeV (?)
- variability in flux, constant slope
- spectral index \( \alpha \)
  \( S(\nu) \sim \nu^{-\alpha} \)

Note:

\( F_\nu \) and \( \nu F_\nu \) representation of SED

\( \nu F_\nu \) corresponds to energy output in that part of the spectrum

SED of 3C 273 (Türler et al. 1999):
jet contribution: dashed, host galaxy: dotted
Extragalactic jets – spectral energy distribution

AGN / blazar spectra

-> model fits to AGN SEDs assuming multiple components: jet, core (inner jet), accretion disk, dust torus, host galaxy, “star burst”, ...

$S(\nu) \sim \nu^{-\alpha}$
core: $\alpha \sim 0$, flat,
jets: $\alpha \sim 0.6$, steep
hot spots: $\alpha \sim 0.5-1.0$

Spitzer observations of powerfull radio sources
(Cleary et al. 2007) modrl fits
Outflows & Jets: Theory & Observations

Extragalactic jets – FR classification

Historical classification:
comparison of radio surface brightness & source size (Fanaroff & Riley 1974):

-> ratio $R_{\text{FR}} = \text{ratio of distance between regions of highest surface brightness to total extent (i.e. faint comp.)}$

-> Two classes:
   - FR-I : $R_{\text{FR}} < \frac{1}{2}$
     "core dominated"
   - FR-II : $R_{\text{FR}} > \frac{1}{2}$
     "lobe dominated"
Extragalactic jets – FR classification

**Historical classification:**

Comparison of radio surface brightness & source size (Fanaroff & Riley 1974):

- Ratio $R_{FR} = \frac{\text{distance between regions of highest surface brightness}}{\text{total extent}}$

- Two classes:
  - FR-I: $R_{FR} < \frac{1}{2}$
    - "core dominated"
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    - "lobe dominated"

FR-II example Cyg A

-> FR correlation w/spectral radio luminosity
dividing line $L_R \sim R^{2\text{opt}}$

Distribution of FR-I, FR-II radio galaxies as function of their 1400 MHz radio luminosity & absolute B magnitude (from Owen and Ledlow 1994)
FR-I / FR-II physical distinction:

Jets in FR-II galaxies:
- generally smooth
- often one-sided,
- end in hotspots in well-separated lobes

Jets in FR-I galaxies:
- two-sided
- radio structures often distorted & plume-like

Smoothness of FR-II jets:
indicative of highly supersonic flows,

-> FR-I jets thought to be subsonic (makes them amenable to distortions by interaction with ambient medium)
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Extragalactic jets – classification

FR-I / FR-II physical distinction:

Two possibilities for difference in jet speed:

(1) jets in radio galaxies & quasars produced similarly by central engine - always emerge supersonic - slowed down if sufficient interaction w/ ambient medium

(2) engines that power FR-I & FR-II sources different in nature - produce subsonic or supersonic jets, respectively

“Models based on both assumptions have been proposed -> but development is suggestive only, -> theoretical concepts & observational consequences involved remain to be explored”


-> Note: quote from 1999 but still true today
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Extragalactic jets – classification

FR-I / FR-II physical distinction:

**Hypothesis 1: environment** (De Young 1993 & others)

a) for given radio luminosity
   -> optical luminosity limit separating FRI / FRII
   -> transitions occur at fixed radio luminosity
   -> no change in central engine producing the radio
   -> difference FRI/II must be environmental

b) suggests that FR-I jets decelerated at short distance outside production region:
   -> little interaction before significant deceleration begins
   -> low luminosity
   -> explains gap, often found between nucleus & base of FR-I jets
   -> after deceleration, jets must travel relatively unimpeded over large distances,
     (otherwise outflow would cease completely)

c) deceleration by momentum transfer from jet to dense ambient gas
d) dense ambient medium expected, infall of gas into central region (many ways ...)
e) active star formation expected: 1) enhanced density of central region, 2) jet induced
   -> FR-I central regions bluer than those in FR-II
   -> test requires good SNR images in colors of many radio galaxies: not yet made
Extragalactic jets – classification

FR-I / FR-II physical distinction:

Hypothesis 2: central engine: main arguments from correlations of radio luminosity, emission line luminosity & host galaxy magnitude (Baum et al. 1995)

a) with same host galaxy absolute magnitude or radio luminosity, FR-II produce 10x more optical line emission than FR-I.
   - FR-II much brighter in line emission than radio-quiet galaxies of same optical magnitude
   - FR-I & radio-quiet galaxies of same magnitude have comparable line emission
b) FR-I emission line luminosity correlates with absolute magnitude, not seen for FR-II
c) FR-II produce much more line emission than FR-I of the same total or core radio luminosity
d) emission line luminosity in both types correlated with total & core radio luminosities, but the regression line for each type has a different slope and intercept
e) strong correlation between core & total radio luminosities for both types.
   - continuity in the distribution of the two galaxy types in log($L_{RC}$ / $L_{R, ext}$) vs log $L_R$-plane
   (L$_{RC}$ and L$_{R, ext}$ are core & extended radio luminosity (408 MHz), $L_R = L_{RC} + L_{R, ext}$).
   - regression lines fitted separately to FR-I & FR-II in this plane are not much different.

suggestion: FR-I arise when accretion rate to BH is low & BH rotates slow
FR-II arise when accretion rate is high & BH spins more rapidly

-> BH spin makes difference in jets: subsonic jets for low spin, supersonic jets for high spin
-> different jet properties -> different levels of interaction with ambient medium
   -> causing different radio morphologies
Extragalactic jets – spectral energy distribution (SED)

AGN / blazar spectra

- two peaks (FIR, MeV)
- break in radio, dip in UV/X-ray, cut-off for TeV (?)
- variability in flux, constant slope
- spectral index $\alpha \rightarrow S(\nu) \sim \nu^{-\alpha}$
  - core: $\alpha \sim 0$ (flat)
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  - hot spots: $\alpha \sim 0.5...1.0$

SEDs of NGC 6251, Cen A & M 87, compared to blazar sequence (Ghisellini et al. 2005)
Outflows & Jets: Theory & Observations

Radiation processes in AGN: Synchrotron emission

-> predicted as physical process by Schwinger (1949)
-> predicted as astrophysical application: Alfven & Herlofson '50, Shklovsky '53
-> observed by Burbidge in M87 (1956)

Synchrotron radiation of single particle:

-> relativistic electron (proton): “hot”; thermal motion with relativistic speed
-> charges gyrate in magnetic field:
   -> non-relativistic case: cyclotron radiation: radiation frequency = gyro frequency
      \[ \omega_G = \frac{eB}{m_e c} = 1.8 \times 10^7 \left( \frac{B}{1 \text{G}} \right) \text{rad s}^{-1} \]
   -> relativistic case: synchrotron radiation:

(1) Lorentzfactor: \( m_e \rightarrow \gamma m_e \)

(2) “Beaming” into opening angle \( \sim \gamma^{-1} \) (collimation/amplification in v-direction)
   -> “light house”: beam from electron sweeps over observer

   time scales: emitted puls: \( \Delta t_{em} \sim \gamma^{-1} \frac{\omega}{\gamma^{-1}} = \frac{m_e c}{e B} \)

   observed puls: \( \Delta t_{obs} \sim (1 - \vec{n} \cdot \vec{\beta}) \Delta t_{em} \sim \Delta t_{em} / 2 \gamma^2 \)
   (Taylor expansion of 1-\( \beta \))
Outflows & Jets: Theory & Observations

Radiation processes in AGN: Synchrotron

(3) Fourier transformation of puls

\[ \nu_c \sim \Delta t_{obs}^{-1} \sim \gamma^2 \omega_G \sim \gamma^2 \left( \frac{B}{1 \text{G}} \right) \text{MHz} \]

Radiation power: \( \nu \) small: \( P \sim \nu^{1/3} \), \( \nu \) large: \( P \sim \exp\left(-\frac{\nu}{\nu_c}\right) \), maximum @ 0.29 \( \nu_c \)

Dipole radiation of accelerated electron: \( P \sim |\vec{E}|^2 \), with \( \vec{E} = \frac{e \beta_{\text{perp}}}{r c} \)

Power: non-relativistic (Larmor formula): \( P = \frac{2 e^2 |\vec{\beta}|^2}{3 c} \)

relativistic: \( P = \frac{2 e^2 \gamma^6}{3 c} \left[ |\vec{\beta}|^2 - (\beta \times \dot{\beta})^2 \right] = 2 c \sigma_T \gamma^2 \beta_{\text{perp}}^2 \frac{B^2}{3 \pi} \)

Cooling time, synchrotron losses: \( t_{\text{cool}} = \frac{\gamma m_e c^2}{P} \sim 6 \times 10^8 \left( \frac{B}{1 \text{G}} \right)^{-3/2} \left( \frac{\nu}{\text{MHz}} \right)^{-1/2} \)

Number values for: extended radio source / radio jet / inner accretion disk:

\[ B [\text{G}] = 10^{-5}, 10^{-3}, 10^3 \]; \( \nu_c [\text{Hz}] = 10^9, 10^9, 10^{16} \); \( \gamma = 10^4, 10^3, 10^{3.5} \)
\[ t_{\text{cool}} [\text{yr}] = 10^7, 10^4, 10^8 \]; \( t_{\text{dyn}} [\text{yr}] = 10^8, 10^4, 1 \)
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Radiation processes in AGN: Synchrotron emission

(4) **Synchrotron power law:** synchrotron spectrum of many electrons:

- non-thermal synchrotron radiation:
  - power law for electron energy distribution: \( N_\gamma = K \gamma^{-s} \)
  - valid for certain energy scale: “cut-off” at \( \gamma_{\text{min}}, \gamma_{\text{max}} \)
  - maximum emission of each electron at \( \nu_c \sim \gamma^2 \omega_G \)

- radiation power of single electron: \( P_\nu \sim \Phi_\nu \), \( \Phi_\nu(\gamma) = \delta(\nu - \nu_c) \)

- integration over electron distribution -> total spectrum:
  - spectral emissivity / volume: \( j_\nu \sim \int N_\gamma P_\gamma d\gamma \) -> radiation power:

- power law electron distribution -> power law spectral energy distribution:
  - spectral index:
    \( \alpha = (s - 1)/2 \)

- examples:
  - extended radio sources: \( \alpha \approx 0.7, \ s \approx 24 \)
  - radio jets: \( \alpha \approx 0.5 \)

\[
\text{Integration over electron distribution} \\
\text{-> total spectrum} \\
\text{-> spectral emissivity / volume: } j_\nu \sim \int N_\gamma P_\gamma d\gamma \\
\text{-> radiation power: } P_\nu \sim K B^{1+\alpha} \nu^{-\alpha}
\]
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Radiation processes in AGN: Synchrotron

(5) Polarization:

- synchrotron radiation linearly polarized up to $P = 75\%$
- elliptical polarisation only for anisotropic case
- P vector perpendicular to B
- synchrotron spectrum: for power law $N_\gamma = K \gamma^{-s}$

  polarization degree $P = \frac{s+1}{s+7/3}$, $P = 69\%$ for $s = 2$

- Faraday rotation (Faraday 1845):
  linear polarisation = left + right handed circular polarisation:
  - left + right circularly polarized EM waves experience different refraction in ionized medium
  - propagate with different phase speed
  - net polarization vector rotates by angle $\phi = RM \lambda^2$

rotation measure: $RM = \frac{e^3}{2 \pi m_e^2 c^4} \int_{\text{los}} B \parallel n_e \, ds = 0.81 \int_{\text{los}} B \parallel n_e \, ds$

Note: 1) RM frequency-dependent -> observe various $\lambda$ may give intrinsic angle
2) estimate of B or $n_e$ may provide $n_e$ or B, respectively
(6) **Synchrotron self-absorption:**

For compact radio sources, the emitting medium may absorb the emitted radiation:

- Radiation flux: \( S_\nu = \int \left( \frac{j_\nu}{4\pi D^2} \right) dV \), intensity conserved along ray: \( S_\nu = \int I_\nu d\Omega \)

- Optically thick case: intensity is conserved, source function: \( I_\nu = j_\nu / 4\pi \rho \kappa_\nu \)

- Radiation in source is anisotropic, break frequency \( \nu_b \)

- Source is optically thick for \( \nu \ll \nu_b \), optically thin for \( \nu \gg \nu_b \)

- "Brightness temperature" corresponds to a blackbody of intensity \( I_\nu \) in Rayleigh-Jeans tail of Planck spectrum:

\[
T_B \equiv \frac{I_\nu c^2}{2k_B \nu^2}
\]

- Thermodynamically we have:

\[
T_B(\nu) \approx \frac{\nu m_e c^2}{3k_B} \simeq 10^9 \left( \frac{\nu}{\text{MHz}} \right)^{1/2} \left( \frac{B}{1\text{G}} \right)^{-1/2} \text{K}
\]

- Self-absorbed synchrotron radiation flux:

\[
S_\nu \sim T_B \nu^{5/2}
\]

- Explains observed FIR cut-off in radio-quiet quasars (radio lobes are optically thin)
Extragalactic jets – spectral energy distribution

AGN / blazar spectra

-> model fits to AGN SEDs assuming multiple components: jet, core, accretion disk, dust torus, host galaxy, “star burst”, ...

Spitzer observations of powerfull radio sources (Cleary et al. 2007) modrl fits
Outflows & Jets: Theory & Observations

**Radiation processes in AGN: Compton scattering**

**1) Thomson scattering:**

Low energy regime ~ **Rayleigh scattering**: frequency conservation

-> electron accelerated by photon -> radiation power: \( P \sim |E|^2 \), with \( E = \frac{e \beta_{\perp}}{rc} \)

-> differential scattering cross section,
   photon in \( n \)-direction (polarised in \( e \)-direction):
   \[
   \frac{d\sigma}{d\Omega} = r_e^2 |\vec{e} \cdot \vec{e}'| = \frac{1}{2} r_e^2 \left( 1 + (\vec{n} \cdot \vec{n}')^2 \right)
   \]

-> averaging over \( (\vec{n} \cdot \vec{n}') \) -> cross section: \( \sigma_T = 6.652 \times 10^{-25} \, cm^2 \)

-> for \( \tau_T \ll 1 \): scattering probability

   for \( \tau_T \gg 1 \) (optically thick): escape time scale
Radiation processes in AGN: Compton scattering

(2) Compton scattering:

- Electron recoil if \( h \nu \approx m_e c^2 \) scattering with \( h \nu' \rightarrow h \nu \) electron gains ...
- Compton scattering
  (consider energy & momentum conservation):

\[
\nu = \frac{m_e c^2 \nu'}{m_e c^2 + h \nu' (1 - \hat{n} \cdot \hat{n}')}
\]

- Frequency shift:

\[
\frac{\Delta \nu}{\nu} = -\frac{h \nu}{m_e c^2} (1 - \cos \theta),
\]

angle average:

\[
\overline{\Delta \nu} \approx -\frac{h \nu}{m_e c^2}, \quad (h \nu \ll m_e c^2)
\]

Example: at \( h \nu = 6.4 \text{ keV} \) shift is 0.2 keV
(2) **Compton scattering**: Klein-Nishina cross section decreased due to $\Delta \nu$:

$$\sigma \simeq \frac{3}{8} \sigma_T \frac{m_e c^2}{h \nu} \left( \frac{1}{2} + \ln \left( \frac{2h \nu}{m_e c^2} \right) \right), \quad h \nu \gg m_e c^2 \quad \sigma \simeq \left( 1 - \frac{2h \nu}{m_e c^2} \right), \quad h \nu \ll m_e c^2$$
Radiation processes in AGN: Compton scattering

(2) Compton scattering: Klein-Nishina cross section angular distribution:

\[
\frac{d\sigma}{d\Omega} = \frac{3}{16\pi} \left( \frac{h\nu'}{h\nu} \right)^2 \left( \frac{h\nu}{h\nu'} + \frac{h\nu'}{h\nu} \sin^2\theta \right)
\]
Inverse Compton:

- Astrophysically essential: up-scattering of photons on highly relativistic electrons:
  - Energy gain of photon field: \( P_{\text{comp}} = \frac{4}{3} \sigma_T c \, \gamma^2 \beta^2 U_{\text{rad}}, \quad \gamma \gg 1 \)

  - Averaged scattered photon frequency: \( \bar{\nu} = \frac{4}{3} \gamma^2 \nu' \)

- Compare to synchrotron power: \( P_{\text{sync}} = \frac{4}{3} \sigma_T c \, \gamma^2 \beta^2 U_{\text{magn}} \)

- Both have same electron energy dependence: \( \frac{P_{\text{comp}}}{P_{\text{sync}}} = \frac{U_{\text{rad}}}{U_{\text{magn}}} \)

Synchrotron - Self Compton radiation:

- Inverse Compton up-scattering of synchrotron photons (in radio cores)

- Scattered flux from integrating synchrotron spectrum and electron distribution with delta function:

\[
S_{\text{comp}}(\nu) = \int d\nu' \nu'^{-\alpha} \int d\gamma \gamma^{-s} \delta(\nu - \frac{4}{3} \gamma^2 \nu') \sim \int d\nu' \nu'^{-\alpha-1}
\]

- Spectral index remains similar: \( \alpha = (s - 1)/2 \)
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Radiation processes in AGN: Inverse Compton scattering

(4) Synchrotron - self compton radiation:

Example:

Synchrotron (peak ~ $10^{19}$ Hz) & synchrotron self-Compton (peak ~ $10^{27}$ Hz) spectra of Mkn 501 (Konopelko et al 2003)

Ordinate $\nu F_{\nu}$ proportional to flux density per logarithmic frequency range

$\Rightarrow$ relative heights of peaks reflect their relative contributions to $U_{rad}$
Radiation processes in AGN: Comptonisation

(5) Comptonisation:

- energy exchange between photons and electrons by inverse Compton scattering

- thermal equilibrium = Comptonisation

- heating of electrons by photons:

\[ W_{pe} = n_e \sigma_T c \int d\nu U_{rad} \frac{h\nu}{m_e c^2}, \quad h\nu \ll m_e c^2 \]

- energy transfer to photons:

  - frequency shift, in average:

  \[ \frac{\Delta\nu}{\nu} \approx - \frac{h\nu}{m_e c^2} \]

  - cooling rate of electrons:

\[ W_{ep} = n_e \sigma_T c \int d\nu U_{rad} \frac{4k_B T}{m_e c^2} \]

- net power gain of photon field:

\[ P_{comp} = \frac{4}{3} \sigma_T c \gamma^2 \beta^2 U_{rad} \]
(5) **Comptonisation:**

thermal equilibrium between photons & electrons by inverse Compton scattering

\[
\text{synchrotron power was: } P_{\text{sync}} = \frac{4}{3} \sigma_T c \gamma^2 \beta^2 U_{\text{mag}} \quad \Rightarrow \quad \frac{P_{\text{comp}}}{P_{\text{sync}}} = \frac{U_{\text{rad}}}{U_{\text{mag}}}
\]

-> in AGN: equilibrium temperature determined by \( U_{\text{rad}} \gg U_{\text{kin}} \) and

\[
T_C = \frac{h \bar{\nu}}{4k_B}, \quad \bar{\nu} \equiv \frac{\int d\nu \nu U_\nu}{\int d\nu U_\nu}
\]

(time scale for comptonization: \( t_C \approx \frac{m_e c^2}{\sigma_T U} \))

-> exact treatment by Kompaneets equation

**Compton catastrophe:** for \( U_{\text{rad}} > U_{\text{mag}} \) \( \Rightarrow \) \( P_{\text{comp}} > P_{\text{sync}} \)

-> (synchrotron) photons strongly amplified \( \Rightarrow \) efficient electron cooling by IC

-> brightness temperature of radio sources limited to \( 10^{12} \) K

**brightness temperature** = temperature a blackbody would need to emit radiation of the observed intensity at a given frequency: \( I_\nu = B_\nu (T_B) \)
Extragalactic jets – spectral energy distribution

Example: AGN / blazar spectra

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  core: $\alpha \approx 0$ (flat), jets: $\alpha \approx 0.6$ (steep)
  hot spots: $\alpha \sim 0.5...1.0$

SEDs of RGB J0152+017 (BL Lac)

- quasi-simultaneous observations (color)
  by HESS (Gamma), Swift & RXTE (X-ray),
  ATOM (optical), Nancay (radio)

- SSC model (solid):
  X-rays & gamma rays from synchrotron radiation & inverse Compton
  (electrons in volume $\sim 10^{15}$ cm,
  at highly relativistic speed).

- additional synchrotron component from more extended region added
to explain radio flux.

(from HESS webpage)
Proper motion of jet knots:

Example 1:
M87 inner knots by HST:
\[ v \sim 6c \]

*apparent superluminal motion*  
(Biretta et al. 1999)

Note: optical resolution sufficient for nearest extragalactic jet source (16 Mpc),
\[ \rightarrow \text{other sources: radio interferometry} \]
Outflows & Jets: Theory & Observations

Extragalactic jets – proper motion

Velocity of extragalactic jets
Proper motion of jet knots
Example 2:
Blazars & Quasars:
   jets pointing towards the observer;
   high variability, strong beaming

3C 345: ~7c (period 5 yrs)
0827+243: Lorentz factor ~20
Note: highest resolution with VLBA radio interferometry
Jet of 3C279

time series 1995 - 2001:

ejection of “knots” from core correlated with luminosity flares

-> “knots” in radio
-> flares in IR, X

-> knot velocity ~ 4c
Comparison of models with observations:

MHD provides time-dependent dynamics of propagation

Radiation field follows from density, velocity etc

$\Rightarrow$ Intensity maps to be compared with observations

Simulation of highly resolved radio observations of 3C279.

time evolution of radio knots at 22 GHz.
resolution 0.15 mas. Jet velocity $5c$ (Lindfors et al. 2006)
Outflows & Jets: Theory & Observations
Lecture plan & schedule

Summer term 2011
Henrik Beuther & Christian Fendt

15.04 Today: Introduction & Overview ("H.B." & C.F.)
29.04 Definitions, parameters, basic observations (H.B.)
06.05 Basic theoretical concepts & models; MHD (C.F.)
13.05 MHD & plasma physics; applications (C.F.)
20.05 Radiation processes (H.B.)
27.05 Observational properties of accretion disks (H.B.)
03.06 Accretion disk theory and jet launching (C.F.)
10.06 Theory of interactions: entrainment, Instabilities, shocks (C.F.)
17.06 Outflow-disk connection, outflow entrainment (H.B.)
24.06 Outflow-ISM interaction, outflow chemistry (H.B.)
01.07 Outflows from massive star-forming regions (H.B.)
08.07 Extragalactic jets: observations, radiation mechanisms (C.F.)

15.07 Some aspects of relativistic jet theory (C.F.)