Outflows & Jets: Theory & Observations

Lecture winter term 2008/2009

Henrik Beuther & Christian Fendt
Outflows & Jets: Theory & Observations

10.10 Introduction & Overview ("H.B." & C.F.)
17.10 Definitions, parameters, basic observations (H.B.)
24.10 Basic theoretical concepts & models I (C.F.): Astrophysical models, MHD
31.10 Basic theoretical concepts & models II (C.F.): MHD, derivations, applications
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14.11 Accretion, accretion disk theory and jet launching (C.F.)
21.11 Outflow-disk connection, outflow entrainment (H.B.)
28.11 Outflow-ISM interaction, outflow chemistry (H.B.)
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30.01 Summary, Outlook, Questions (H.B. & C.F.)
Outflows & Jets: Theory & Observations

Radiation processes in jets & outflows

Jets & forbidden emission lines (FEL)

Protostellar jets discovered in optical forbidden emission lines

Examples: DG Tau (Mundt & Fried 1983), HH34 (Bührke et al. 1988)

Associated to / interrelated with HH objects:

= nebulous (narrow) emission line regiones (Herbig and Haro in the 40ies),
  see online catalogue by Bo Reipurth, ~400 entries, http://casa.colorado.edu/hhcat/
= shock-excited emission in dilute gas (Schwartz 1975, Raymond 1979)
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Example: HH 47 time series; red: S[II], green: Hα (Pat Hartigan)
(see http://sparky.rice.edu/~hartigan/movies.html for more movies)
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Radiation processes in jets & outflows

Jets & FEL

Example: HL Tau (edge-on TTauri):
Blue-shifted, double-peaked
forbidden-line profiles:
- one component blue-shifted by 194 km/s relative to photospheric spectrum;
other component same radial velocity as absorption spectrum;
  -> indication for disk-jet system seen at intermediate inclinations.
- relative strength of two profile components varies greatly between different lines
  -> indicating that two components originate in different volumes.
- blue-shifted peak unresolved -> originates in directly observed narrow jet intersected slit
- region producing the red peak is extended, shows about the same angular extension as the continuum.
- low-velocity emission -> originates in rarefied extended emission region;
slight blue-shift ~ 5 km/s relative to the photospheric spectrum caused either by slow outflow or by scattering in a slowly moving medium.

(Appenzeller et al. 2005)
Outflows & Jets: Theory & Observations

Radiation processes in jets & outflows

Jets & forbidden emission lines (FEL)

(Mundt & Fried 1983)

(Buehrke et al. 1988)
Forbidden emission lines

- shock exited / heated
- low excitation FELs (in protostellar jets):
  - [SII], [Ni], [NII], [OII], [OIII], [FeI]
  - critical conditions for existence
- optically thin
- narrow lines
- tracer of jet dynamics:
  - example DG Tau (Solf & Böhm 1993)
  - with HST:
    - position-velocity diagrams along slit positions:
      - (sometimes now called spectro-astrometry)
  - 'a' (along the jet) or 'b' (across the jet) in different FELs
    - radial velocity (redshift)
    - temperature, density (line ratios, excitation)
  - jet components in velocity space / jet dynamics
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Radiation processes in jets & outflows

Forbidden emission lines

FEL analysis DG Tau (Solf & Böhm 93)

- > three flow components:

A: low velocity, -43km/s,
- narrow, unresolved, close to star, 0”.2
- prominent in [OI], [SII], not in [NII]
- \( \langle N_e \rangle \) > 10000/cm\(^3\) [SII]

B: intermediate / high velocities, 120-340km/s
- broad, large spatial extend
- triangular \( \rightarrow \) v-dispersion increases
- \( \langle N_e \rangle \) ~ 2400, up to 8000/cm\(^3\)
- only B is seen in [NII];

C: high velocity (250km/s centroid),
- close to star, separation 0”.2
- broad, distinct from B
- bright in [OI], no [SII], [NII]
- short extension ~ 0”.73
Forbidden emission lines

Why forbidden?

$\rightarrow$ radiative transition to certain atomic energy state “not allowed” (probability is very very low) by selection rules of certain classification scheme (as eg. for L-S coupling)

$\rightarrow$ (electric) dipole selection rules for many electrons atom:

$\Delta S = 0$ (spin)

$\Delta L = 0, +1, -1$ (orbital angular momentum)

$\Delta J = 0, +1, -1$ (total angular momentum)

$\Delta m = 0, +1, -1$ polarized light (magnetic quantum number m)

$\rightarrow$ higher order transitions if electric dipole transition “forbidden”:

- 2$^{nd}$ order electric, magnetic dipole

$\rightarrow$ transition rates / radiative life times

$E_1$: $10^8 .. 10^9$ /s - 1-10 ns

$E_2 / M_1$: $10^3 .. 10^6$ /s - 1$\mu$s - 1ms

$\rightarrow$ line width for decay time $\tau$ is $\Delta v = 1 / 2\pi \tau$; Lorentzian line profile (several orders of mag narrower than Gaussian due to Doppler / collisional broadening)
Forbidden emission lines

How to excite FEL upper levels?

-> collisional excitation / de-excitation:

-> excitation cross section: function of e- velocity:
$$\sigma(1,2 ; \nu) \sim \frac{1}{\nu^2} \text{ for } \frac{1}{2} m \nu^2 > h \nu(2,1)$$

-> definition collision strength:
$$\sigma(1,2 ; \nu) = \frac{\pi h^2}{m^2 \nu^2} \frac{\Omega(1,2)}{\omega_1}$$

collision strength $\Omega = \Omega(\nu)$ to be calculated from quantum mechanics

-> similar cross section for collisional de-excitation in thermodynamic equilibrium (TE)
$$\sigma(2,1 ; \nu_2) = \sigma(1,2 ; \nu_1) \frac{\omega_1}{\omega_2} \left( \frac{\nu_1}{\nu_2} \right) ; \quad \omega_i \text{ is statistical weight of level } i,$$

$v1$ and $v2$ related by
$$v_1^2 = v_2^2 + 2 \frac{h}{m} \nu(2,1)$$

-> microscopically balanced state in TE:
$$N_e N_1 v_1 \sigma_{12}(v_1) f(v_1) dv_1 = N_e N_2 v_2 \sigma_{21}(v_2) f(v_2) dv_2$$

-> Boltzmann:
$$\frac{N_2}{N_1} = \frac{\omega_2}{\omega_1} \exp\left(-\frac{h \nu}{kT}\right)$$
### Forbidden emission lines, collision strength $\Omega$, 

- Total collisional de-excitation rate per unit volume

$$N_e N_2 q_{21} \equiv N_e N_2 \int_0^\infty \nu \sigma_{21}(\nu) f(\nu) d\nu = N_e N_2 \frac{8.629 \times 10^{-6}}{T^{1/2}} \frac{\Omega(1,2)}{\omega_2}$$

with average collision strength

$$\Omega(1,2) = \int_0^\infty \Omega(1,2;E) \exp(-E/kT) d(E/kT); E = 0.5 m v^2$$

- Similar collisional excitation rate $N_e N_1 q_{12}$ where

$$q_{12} = \frac{\omega_2}{\omega_1} \exp(-h \nu/kT)$$

- Example 3p$^3$ ion configurations

(Czyzak et al. 68):

<table>
<thead>
<tr>
<th>Ion</th>
<th>$k_{3^2}$</th>
<th>$\Omega(3P_0, 3P_1)$</th>
<th>$\Omega(3P_0, 3P_2)$</th>
<th>$\Omega(3P_1, 3P_2)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>N$^+$</td>
<td>0.0</td>
<td>0.401</td>
<td>0.279</td>
<td>1.128</td>
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<tr>
<td></td>
<td>0.1</td>
<td>0.424</td>
<td>0.282</td>
<td>1.164</td>
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<tr>
<td>O$^{+2}$</td>
<td>0.0</td>
<td>0.376</td>
<td>0.213</td>
<td>0.948</td>
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<tr>
<td></td>
<td>0.4</td>
<td>0.391</td>
<td>0.207</td>
<td>0.954</td>
</tr>
<tr>
<td>Ne$^{+2}$</td>
<td>0.0</td>
<td>0.185</td>
<td>0.131</td>
<td>0.527</td>
</tr>
<tr>
<td></td>
<td>0.4</td>
<td>0.200</td>
<td>0.134</td>
<td>0.551</td>
</tr>
</tbody>
</table>
Forbidden emission lines

- transition probabilities & line wavelength (taken e.g. from Garstang 1968)

<table>
<thead>
<tr>
<th>Transition</th>
<th>S\textsc{ii}</th>
<th>C\textsc{iii}</th>
<th>A\textsc{riv}</th>
<th>K\textsc{v}</th>
</tr>
</thead>
<tbody>
<tr>
<td>(^2\text{P}_1\rightarrow^2\text{P}_1)</td>
<td>1.0 \times 10^{-6}</td>
<td>7.6 \times 10^{-6}</td>
<td>5.2 \times 10^{-5}</td>
<td>2.8 \times 10^{-4}</td>
</tr>
<tr>
<td>(^2\text{D}_2\rightarrow^2\text{P}_1)</td>
<td>0.21</td>
<td>0.36</td>
<td>0.67</td>
<td>1.5</td>
</tr>
<tr>
<td></td>
<td>10320.6</td>
<td>8481.6</td>
<td>7237.3</td>
<td>6317</td>
</tr>
<tr>
<td>(^2\text{D}_1\rightarrow^2\text{P}_1)</td>
<td>0.17</td>
<td>0.39</td>
<td>0.91</td>
<td>2.3</td>
</tr>
<tr>
<td></td>
<td>10287.1</td>
<td>8433.7</td>
<td>7170.6</td>
<td>6223</td>
</tr>
<tr>
<td>(^2\text{D}_0\rightarrow^2\text{P}_1)</td>
<td>0.087</td>
<td>0.108</td>
<td>0.122</td>
<td>0.19</td>
</tr>
<tr>
<td></td>
<td>10372.6</td>
<td>8550.5</td>
<td>7332.0</td>
<td>6447</td>
</tr>
<tr>
<td>(^2\text{D}_1\rightarrow^2\text{P}_1)</td>
<td>0.20</td>
<td>0.35</td>
<td>0.68</td>
<td>1.5</td>
</tr>
<tr>
<td></td>
<td>10338.8</td>
<td>8501.8</td>
<td>7262.8</td>
<td>6349</td>
</tr>
<tr>
<td>(^4\text{S}_1\rightarrow^2\text{P}_1)</td>
<td>0.34</td>
<td>0.96</td>
<td>2.55</td>
<td>6.5</td>
</tr>
<tr>
<td></td>
<td>4068.6</td>
<td>3342.9</td>
<td>2854.8</td>
<td>2494.5</td>
</tr>
<tr>
<td>(^4\text{S}_1\rightarrow^2\text{P}_1)</td>
<td>0.134</td>
<td>0.37</td>
<td>0.97</td>
<td>2.4</td>
</tr>
<tr>
<td></td>
<td>4076.4</td>
<td>3353.3</td>
<td>2869.1</td>
<td>2514.5</td>
</tr>
<tr>
<td>(^2\text{D}_2\rightarrow^2\text{D}_1)</td>
<td>3.3 \times 10^{-7}</td>
<td>3.2 \times 10^{-6}</td>
<td>2.3 \times 10^{-5}</td>
<td>1.4 \times 10^{-4}</td>
</tr>
<tr>
<td>(^4\text{S}_1\rightarrow^2\text{D}_2)</td>
<td>4.7 \times 10^{-4}</td>
<td>1.01 \times 10^{-3}</td>
<td>2.2 \times 10^{-3}</td>
<td>6.9 \times 10^{-3}</td>
</tr>
<tr>
<td></td>
<td>6716.4</td>
<td>5517.2</td>
<td>4711.3</td>
<td>4122.6</td>
</tr>
<tr>
<td>(^4\text{S}_1\rightarrow^2\text{D}_1)</td>
<td>3.0 \times 10^{-4}</td>
<td>7.0 \times 10^{-3}</td>
<td>0.028</td>
<td>0.11</td>
</tr>
<tr>
<td></td>
<td>6730.8</td>
<td>5537.7</td>
<td>4740.2</td>
<td>4163.3</td>
</tr>
</tbody>
</table>

* From Czyzak and Krueger (1963) for S\textsc{ii}, C\textsc{iii} and A\textsc{riv}. K\textsc{v} calculated by Garstang for inclusion
Forbidden emission lines, cooling rates

- for single excited level & very low density:
  \[ L_C = N_e N_1 q_{12} h \nu_{21} \]

- for higher densities, collisional de-excitation not negligible
  - cooling rate reduced
  - equilibrium, balance between excitation and de-excitation rates

\[ N_e N_1 q_{12} = N_e N_2 q_{21} + N_2 A_{21} \quad ; \quad \frac{N_2}{N_1} = \frac{N_e q_{12}}{A_{21}} \left( \frac{1}{1 + \frac{N_e q_{12}}{A_{21}}} \right) \]

- cooling rate:
  \[ L_C = N_2 A_{21} h \nu_{21} = \frac{N_2}{N_1} = N_e N_1 q_{12} h \nu_{21} \]

- for ions with more levels:
  - collisional and radiative transitions between any of levels
  - take into account excitation & de-excitation cross sections and collision strengths of all levels

- equilibrium equation & collisionally excited cooling rates to be solved:
  \[ \sum_{j \neq i} N_e N_j q_{ji} + \sum_{j > i} N_j A_{ji} = \sum_{j \neq i} N_e N_i q_{ij} + \sum_{j < i} N_i A_{ji} \quad ; \quad \sum_j N_j = N \]

\[ L_C = \sum_i N_i \sum_{j < i} A_{ij} h \nu_{ij} \]

- for low-density limit  \[ \rightarrow \] sum of single level terms
Forbidden emission lines, cooling rates

- for ions with more levels:

- for high-densities or $N_e q_{ij} > \sum_{k<i} A_{ik}$

- collisional de-excitation not negligible -> complete equation to be solved

- for any level a **critical density** exists: $N_{cr}(i) = \frac{\sum_{j<i} A_{ij}}{\sum_{j \neq i} q_{ij}}$

- if $N_e < N_{cr}(i)$: collisional de-excitation of level $i$ is negligible
  if $N_e > N_{cr}(i)$: collisional de-excitation of level $i$ is important

- examples (for $T = 10,000 K$):

<table>
<thead>
<tr>
<th>ion</th>
<th>level</th>
<th>critical density (cm$^{-3}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NII</td>
<td>1D2</td>
<td>$1.8 \times 10^4$</td>
</tr>
<tr>
<td>NII</td>
<td>3P2</td>
<td>$2.6 \times 10^2$</td>
</tr>
<tr>
<td>NII</td>
<td>3P1</td>
<td>$4.1 \times 10$</td>
</tr>
<tr>
<td>OII</td>
<td>3D3/2</td>
<td>$3.3 \times 10^3$</td>
</tr>
<tr>
<td>OII</td>
<td>2D5/2</td>
<td>$6.3 \times 10^2$</td>
</tr>
</tbody>
</table>
Forbidden emission lines

Critical e- density: line upper state equally de-excited by collisions & radiative decays

-> e.g. [OI] λ6300 critical density Ncr ~ 10^6 /cm^3

-> ratio with [NI] λ6300, [NII] λ6583, [SII] λ6731 declines for high densities, as those are collisionally surpressed for Ne > 10^4/cm^3

-> ratio with [CI] λ8727, [OII] λ7319, [SII] λ4069 rise towards high densities, as those have Ncr > 10^6/cm^3

( Hamann 1994 )
Outflows & Jets: Theory & Observations

Radiation processes in jets & outflows

**FEL**

intensity ratio:

-> tracer for
temperature & density

Hamann 1994

for young stars

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**Fig. 7.**—Line ratios of [C I], [N I], [S II], and [O II] are plotted against electron density for the temperatures, $T_e = 9000, 12,000, 15,000,$ and $20,000$ K, with $T_e$ increasing from bottom to top. [O II] $\lambda 7319$ and [N I] $\lambda 5200$ and $\lambda 10400$ represent the summed flux in these multiplets (see Fig. 5 caption).
**Outflows & Jets: Theory & Observations**

**Radiation processes in jets & outflows**

**FEL** intensity ratio as tracer for temperature & density
e.g. \([\text{[O]}\text{I}] \lambda 5577\) (solid), \([\text{[S]}\text{II}] \lambda 6731\) (dash-dotted) & \([\text{[S]}\text{II}] \lambda\lambda(4069+4076)\) (dashed) to \([\text{[O]}\text{I}] \lambda 6300\) as function of electron density \(N_e\) & temperature \(T\), all optically thin (Kwan & Tademaru 95)

- \(N_e\) range where \([\text{[S]}\text{II}] \lambda 6731\) strong not compatible with \([\text{[O]}\text{I}] \lambda 5577\) strong
- \([\text{[S]}\text{II}] \lambda 6731\) not good indicator of \([\text{[O]}\text{I}] \lambda 5577\) emission
- strength of \([\text{[S]}\text{II}] \lambda\lambda(4069+4076)\) to constrain \(T\) for \([\text{[O]}\text{I}] \lambda 5577\) regions
- for \(N_e > 10^6\):
  - \([\text{[S]}\text{II}] \lambda 4076 / \lambda 4069 \sim 0.22 \sim \text{const.}\)
  - \([\text{[S]}\text{II}] \lambda\lambda(4069+4076)\) have critical densities for collisional de-excitation as \([\text{[O]}\text{I}] \lambda 6300\)
- comparison to observations:
  - \([\text{[O]}\text{I}] \lambda 5577 / \lambda 6300 \sim 0.1 ... 1.0\)
    for low velocity component of wind/jet
- lower limit on \(N_e = 3 \times 10^6 / \text{cm}^3\) at \(T = 10^4\) K
  to \(N_e = 2 \times 10^8 / \text{cm}^3\) at \(T = 4.5 \times 10^3\) K
Outflows & Jets: Theory & Observations

Radiation processes in jets & outflows

**FEL** intensity ratio -> measure of jet/wind mass loss rate:

FEL analysis provides electron densities:
- Real gas density higher, depending on ionisation (temperature):
  \[ \frac{N(H)}{N(e)} \approx 1400 \text{ at } T = 9.000 \text{K}, \sim 60 \text{ at } T = 11.000 \text{K}, \]
  \[ \sim 6.4 \text{ at } T = 13.000 \text{K} \text{ (Hamann 94)} \]

Example Mundt et al. 1987:
- HH34 jet e- densities typically 400 – 2000 / cm$^3$ (based on [SII] 6716 / 6731 line ratio) using Dopita (1978) shock models -> jet densities ~ 20 – 100 H-atoms / cm$^3$
- jet mass loss rates $\frac{dM}{dt} = 0.05 – 2 \times 10^{-8} \text{ M}_\odot/\text{year}$

Example Hartigan et al. 1994:
- assumption $N(H) = N(e)$
  - derived jet mass flow rate seems too low to momentum-drive molecular outflows!
  - improve shock modeling to get pre-shock densities from post-shock e- density
  - shock velocities ~ 30 km/s
  - ionisation fraction ~2%, considerably smaller than previous estimates
  - jet mass loss rates $\frac{dM}{dt} > 2 \times 10^{-7} \text{ M}_\odot/\text{year}$
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Radiation processes in jets & outflows

**FEL** intensity ratio:

\[ \text{measure of jet/wind mass flux:} \]

(Hartigan, Morse, & Raymond 94)

**Shock models**

![Graph](image)

**Fig. 1.**—The temperature \( T \) (dotted line), electron density \( N_e \) (short-dashed line), ionization fraction \( I = N_e/(N_{\text{ion}} + N_{\text{neutral}}) \) (solid line), the compression \( C = N_{\text{total}}/N_{\text{preshock}} \) (long-dashed line), and the \([\text{S II}] \) \( \lambda \lambda 6716 + 6731 \) emission (heavy solid line) appear as a function of distance \( x \) behind the shock front for a 35 km s\(^{-1}\) shock (top), and a 70 km s\(^{-1}\) shock (bottom). The curve labeled \([\text{S II}] \) is \( \epsilon[\text{S II}] \times x \), where \( \epsilon[\text{S II}] \) is the emissivity (cm\(^3\) s\(^{-1}\)) plotted vs. log (\( x \)); this quantity is proportional to the total amount of \([\text{S II}] \) emission. The \([\text{S II}] \) emission is on a linear scale (right axis) normalized to unity at the peak, and the other variables are on a log scale (left axis). The behavior of these variables is highlighted in the figure.
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