Lecture 16: Winds, Jets and Outflows

HH 212  $\text{H}_2$ (Mc Caughrean & Zinnecker, VLT)
Losing Material from the Outer Disk Through Photoevaporation
Formation & viscous spreading of disk
Formation & viscous spreading of disk
Formation & viscous spreading of disk
Photoevaporation of disks

(Very brief)

Ionization of disk surface creates surface layer of hot gas. If this temperature exceeds escape velocity, then surface layer evaporates.

\[ v_{\text{esc}} \approx \left( \frac{GM}{r} \right)^{1/2} \]

Evaporation proceeds for radii beyond:

\[ r \geq \frac{GM}{c_{\text{SHII}}^2} \equiv r_{\text{gr}} \]
The Edge of The Solar System:
Evaporation of Disks by UV Radiation

Center of Orion Nebula

Hot O and B-type stars produce powerful UV radiation field.

Young disk bathed in UV light.
Why is there an Edge to the Solar System: Evaporation of Disks by UV Radiation

As fine dust particles clump together deep inside the protoplanetary disk, ultraviolet radiation from a nearby hot star eats away at the disk. The outer portions of the gas bubble are then heated and removed by energetic ultraviolet radiation. Material falling from the disk toward the central object fuels twin gas jets.
Losing Material from the Inner Disk through Accretion and Outflow
Magnetospheric accretion

Free-fall and accretion shock

From $r_A$ down to star: matter is in supersonic free-fall.

Near the star the matter gets to a halt in a stand-off shock.

Shock velocity:

$$v_s = \sqrt{\frac{2GM}{r_*}} \sqrt{1 - \frac{r_*}{r_i}}$$

Dissipated energy (=accretion luminosity from shock):

$$L_{\text{accr}} = \left(1 - \frac{r_*}{r_i}\right) \frac{G\dot{M}M}{r_*}$$
Bipolar outflows

Jets originate from inner regions of protoplanetary disks

HH 30

Hubble Space Telescope image

200 AU
Magnetically threaded disks

Suppose disk is threaded by magnetic field:

Inward motion of gas in disk drags field inward:

B-field acquires angle with disk
Disk winds


Use cylindrical coordinates r,z

Gravitational potential:

$$\Phi = -\frac{GM}{\sqrt{r^2 + z^2}}$$

Effective gravitational potential along field line (incl. sling-shot effect):

$$\Phi = -\frac{GM}{r_0} \left[ \frac{1}{2} \left( \frac{r}{r_0} \right)^2 + \frac{r_0}{\sqrt{r^2 + z^2}} \right]$$
Disk winds


\[ \Phi = -\frac{GM}{r_0} \left[ \frac{1}{2} \left( \frac{r}{r_0} \right)^2 + \frac{r_0}{\sqrt{r^2 + z^2}} \right] \]

Critical angle: 60 degrees with disk plane. Beyond that: outflow of matter.

Gas will bend field lines
Disk + star: X-wind model of Frank Shu

Shu 1994
Different kinds of Winds

Extended disk wind
Blandford & Payne 1982
Konigl & Pudritz 2000

X-wind
Shu et al. 1994

Stellar wind
Matt & Pudritz 2005,…

Configuration favorable for outflows

Bunching, $\alpha_v > \alpha_d$

Pirated from talk by Marina Romanova
Magnetocentrifugal Winds

Romanova et al. 2005; Ustyugova et al. 2006; Romanova et al. 2009
Jets or Winds?
Wind Blown Cavities
Bipolar Outflows driven by Wind

![Diagram of bipolar outflows driven by wind]

**Fig. 1.**—Geometry for shell of molecular gas, moving at speed $v_s(\theta)$ at position $r_s(\theta)$, as swept up by a protostellar wind moving at speed $v_w(\theta)$ into a molecular cloud core with the density profile given by eq. (1). The observer views the system at an inclination angle $i$ with respect to the rotation axis of the protostellar disk, and residual infall of cloud material onto the disk occurs in those directions near the equatorial plane not affected by the outflow.

Shu et al. 1991
Wind Blown Bubble

Equations for core:

\[ \rho(r, \theta) = \frac{c_s^2}{2\pi Gr^2} Q(\mu) \]  \hspace{1cm} (1)

\[ \int_0^1 Q(\mu) d\mu = 1 \]  \hspace{1cm} (2)

\[ \dot{M} \approx \frac{c_s^3}{G}, \quad \dot{M}_w = f \dot{M} \]  \hspace{1cm} (3)

Equations for wind:

\[ P(r, \theta) = \frac{\dot{M}_w v_w}{4\pi} P(\mu) \]  \hspace{1cm} (4)

\[ \int_0^1 P(\mu) d\mu = 1 \]  \hspace{1cm} (5)
Wind Blown Bubble

Assuming momentum conservation but not energy conservation (snowplot), the mass per steradian, $M_{sr}$, grows

$$\frac{dM_{sr}}{dt} = \frac{c_s^2}{2\pi G}Q(\mu)v_s$$  \hspace{1cm} (6)

And the momentum grows by:

$$\frac{d}{dt}(M_{sr}v_s) = \frac{\dot{M}_w v_w}{4\pi} P(\mu)$$  \hspace{1cm} (7)

Now we balance momentum change per steradian due to wind with ram pressure per steradian

$$v_s \frac{dM_{sr}}{dt} = \frac{c_s^2}{2\pi G}Q(\mu)v_s^2 = \frac{\dot{M}_w v_w}{4\pi} P(\mu)$$  \hspace{1cm} (8)
Wind Blown Bubble

implying

\[ v_s = \left( \frac{\dot{M}_w}{2M} \right)^{1/2} (c_s v_w)^{1/2} \beta(\mu), \text{ where } \beta(\mu) = \left( \frac{P(\mu)}{Q(\mu)} \right)^{1/2} \]  \hspace{1cm} (9)

\[ r_s = (f/2)^{1/2} (c_s v_w)^{1/2} t \beta(\mu) \]  \hspace{1cm} (10)

This gives a "Hubble" law for outflows:

\[ v_s = \frac{r_s}{t} \]  \hspace{1cm} (11)
Creating Jets
Creating Jets: Magnetic field winding - confinement

Magnetic Flux Surfaces
Magnetic Field Lines
Central source
Accretion Disk
Christian Fendt

C. Fendt
Magnetic field winding - confinement

\[ \vec{j} = \frac{c}{4\pi} \nabla \times \vec{B} \]

Right-hand rule: force points inwards

\[ \vec{f} = \frac{1}{c} \vec{j} \times \vec{B} \]
Hydrodynamic confinement in jet:

Shock only reduces the velocity component perpendicular to shock front. Therefore obliquely shocked gas is deflected toward the shock plane.
Hydrodynamic confinement in jet:
Bipolar outflows driven by Jets

Swept-up material (molecular outflow)

Terminal shock

Hydrodynamic confinement?

Hot bubble of old jet material

Magnetic confinement

Magneto-centrifugal launching (<AU scale)
Head of the jet:

- Stand-off shock (most of jet energy dissipated here)
- Contact discontinuity (boundary between jet and external medium)
- Bow shock
- Back flow
- Turbulent mixing between old jet material and swept-up environment (entrainment)
- Shocked external medium gas (molecular outflow)

Jet flow much faster than propagation of bow shock. Jet material much more tenuous than external medium.
Most Likely a Combination of Both
A Unified Models of Jets and Winds (Shang et al 2006)
Rapidly-rotating stars: Propeller regime

Two-component outflow forms
- Conical winds carry most of matter outwards
- Poynting jet carries energy and angular momentum

Romanova et al. 2005; Ustyugova et al. 2006; Romanova et al. 2009
The Propeller Regime

Disk radius > Corotation Axis:
Magnetic field rotating faster than disk

Ustyugova et al. 2006
Outflows at the Propeller Stage:
Conical Winds + Axial Jet

A star spins-down due to axial magnetic jet

Pirated from talk by Marina Romanova
Observed knot movement

Stellar Disk and Jet Motion • HH30

February 1994

January 1995

Reversal Emission

Excursion Mode Emissions

Relative Size of Solar System

Stellar Disk and Jet Motion • HH30

HST • WFPC2

PRC95-24b • ST ScI OPO • June 6, 1995 • C. Burrows (ST ScI), NASA
Observations of Jets and Winds
Herbig-Haro Objects

Discovered independently by George Herbig and Guillermo Haro in 1950s

Small knots of nebulosity in dark clouds

Displayed lines of hydrogen and forbidden lines of [OI], [NII] and [SII].

Now known to be shock ionized nebulae.

More than 400 Herbig Haro (HH) objects are known.

*Only trace a small fraction of the outflowing gas*
Forbidden Lines, Atomic Hydrogen Lines and Molecular Hydrogen Lines

IRAS20126+4104 Knot C

Fig. 5. Spectra of various A-B, P, I-J in the HH83 jet and of the bow shock in wavelength range approx. 5200 Å to 6800 Å. Note the increasing [Sii] 6717/Ha ratio as one moves out along the jet, as well as the changing nebular line ratios, indicating decreasing electron density. The bow shock is pure Ha emission.
Knots are probably internal shocks, where faster knots are crashing into slower knots

[Fe II] + K

Ha + [SII]

NICMOS

WFPC2
HH 212   H$_2$ (Mc Caughrean & Zinnecker  VLT)
HH 46/47 NTT [OII] Hα [SII] = 0.38, 0.65, 0.67 µm
Bally & Reipurth (06 “Birth of Stars & Planets” CUP = BR06)
HH 46/47  Spitzer  
(Noriega-Crespo 04; BR06)
HH 46/47
(Hartigan et al. 05, AJ BR06)

HST 1994
HH 46/47
(Hartigan et al. 05, AJ BR06)

HST 1997
HH 2
HH 1

HST 1997 - 1994
HH 2

HH 1

HST 1997 - 1994
HH 1 jet

HST 1997 - 1994
HH 1

HST 1997 - 1994
HH 2

HST 1997 - 1994
HH 34

HST 1997 - 1994
Molecular Outflows
Molecular Outflows: Line Wings
Bally & Lada 1983
Fig. 13.—Maps of seven high-velocity molecular outflow sources in molecular cloud cores taken from the literature: NGC 2071 (Bally 1982a), L 1551 (Snell, Loren, and Plambeck 1980), GL 490 (Lada and Harvey 1981), Cep A (Rodríguez, Ho, and Moran 1980), HH 7–11 (Snell and Edwards 1981), GL 961 (Lada and Gautier 1982), Orion A (Erickson et al. 1982). Solid lines are blueshifted wings, and dashed lines are the redshifted wings.
Molecular Outflows: Basic Properties
Bally & Lada 1983

<table>
<thead>
<tr>
<th>Source</th>
<th>$R_{\text{max}}$</th>
<th>$R_{\text{min}}$</th>
<th>$(R_{\text{max}}R_{\text{min}})^{1/2}$</th>
<th>$R_{\text{max}}/R_{\text{min}}$</th>
<th>$M$</th>
<th>$\dot{M}V$</th>
<th>$\frac{1}{2}MV^2$</th>
<th>$L_{\text{outflow}}$</th>
<th>$\langle n(H_2) \rangle$</th>
<th>$\int \text{Red Wing}$</th>
<th>$\int \text{Blue Wing}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Orion</td>
<td>0.04</td>
<td>0.04</td>
<td>0.04</td>
<td>1.0</td>
<td>5</td>
<td>1</td>
<td>0.52</td>
<td>$2.0 \times 10^{47}$</td>
<td>2600</td>
<td>$3.8 \times 10^5$</td>
<td>...</td>
</tr>
<tr>
<td>AFGL 490</td>
<td>0.34</td>
<td>0.29</td>
<td>0.31</td>
<td>1.2</td>
<td>14</td>
<td>2.3</td>
<td>0.04</td>
<td>$1.5 \times 10^{47}$</td>
<td>115</td>
<td>$2.3 \times 10^3$</td>
<td>0.70</td>
</tr>
<tr>
<td>AFGL 961</td>
<td>1.18</td>
<td>0.97</td>
<td>1.07</td>
<td>1.2</td>
<td>20</td>
<td>3.4</td>
<td>0.007</td>
<td>$8.0 \times 10^{46}$</td>
<td>11</td>
<td>$0.8 \times 10^2$</td>
<td>3.72</td>
</tr>
<tr>
<td>NGC 2071</td>
<td>0.49</td>
<td>0.28</td>
<td>0.37</td>
<td>1.8</td>
<td>20</td>
<td>3.5</td>
<td>0.06</td>
<td>$2.8 \times 10^{47}$</td>
<td>175</td>
<td>$1.9 \times 10^3$</td>
<td>2.40</td>
</tr>
<tr>
<td>Cep A</td>
<td>0.50</td>
<td>0.08</td>
<td>0.20</td>
<td>6.2</td>
<td>10</td>
<td>6</td>
<td>0.012</td>
<td>$6.2 \times 10^{46}$</td>
<td>25</td>
<td>$6.0 \times 10^3$</td>
<td>2.90</td>
</tr>
<tr>
<td>S140</td>
<td>0.46</td>
<td>0.46</td>
<td>0.46</td>
<td>1.0</td>
<td>64</td>
<td>3</td>
<td>0.06</td>
<td>$2.6 \times 10^{47}$</td>
<td>90.0</td>
<td>$3.2 \times 10^2$</td>
<td>0.91</td>
</tr>
<tr>
<td>L1551</td>
<td>0.42</td>
<td>0.08</td>
<td>0.18</td>
<td>5.2</td>
<td>0.3</td>
<td>7</td>
<td>0.0002</td>
<td>$6.7 \times 10^{43}$</td>
<td>0.2</td>
<td>$2.5 \times 10^2$</td>
<td>0.56</td>
</tr>
<tr>
<td>HH 7–11</td>
<td>0.40</td>
<td>0.21</td>
<td>0.29</td>
<td>1.9</td>
<td>4.0</td>
<td>8</td>
<td>0.004</td>
<td>$1.6 \times 10^{46}$</td>
<td>6.5</td>
<td>$7.9 \times 10^2$</td>
<td>4.26</td>
</tr>
<tr>
<td>HH 24–26</td>
<td>0.25</td>
<td>0.19</td>
<td>0.22</td>
<td>1.3</td>
<td>6.3</td>
<td>8</td>
<td>0.006</td>
<td>$1.4 \times 10^{46}$</td>
<td>6.9</td>
<td>$2.9 \times 10^3$</td>
<td>2.0</td>
</tr>
<tr>
<td>Mon R2</td>
<td>2.09</td>
<td>0.70</td>
<td>1.21</td>
<td>4.0</td>
<td>100</td>
<td>9,10</td>
<td>0.02</td>
<td>$2.3 \times 10^{47}$</td>
<td>24.0</td>
<td>$2.8 \times 10^2$</td>
<td>1.18</td>
</tr>
<tr>
<td>Serpens</td>
<td>1.11</td>
<td>0.65</td>
<td>0.85</td>
<td>1.7</td>
<td>...</td>
<td>10</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>T Tauri</td>
<td>0.15</td>
<td>0.15</td>
<td>0.15</td>
<td>1.0</td>
<td>0.1</td>
<td>11</td>
<td>0.00003</td>
<td>$4.2 \times 10^{43}$</td>
<td>0.01</td>
<td>$1.4 \times 10^2$</td>
<td>...</td>
</tr>
</tbody>
</table>

\[a\text{Source sizes corrected for beam size.}\]

Molecular Outflows: Mechanical Luminosity and Momentum Flux
Bally & Lada 1983

Fig. 16.—Plot of the flow mechanical luminosity vs. total bolometric luminosity of the associated infrared sources. Also shown is the relation $L_{\text{HVF}} = L_*$. 

Fig. 17.—Plot of $MV$ for the flows vs. total bolometric luminosity of the associated infrared sources. Also shown is the relation $MV = L_/C$. 
Molecular Outflow: the "Hubble Law"
NGC 2264 G
Fich & Lada
1998
Distinguishing between Wind and Jet Models
Lee et al. 2001
HH 288:
Contours: CO
(2-1)
Greyscale: H$_2$
HH 211
Contours: CO
(2-1)
VLA 05487: example of wind (Lee et al. 2001)
Distinguishing between Wind and Jet Models

Lee et al. 2001
HH 212: example of jet (Lee et al. 2001)
Detecting *Jets* in Molecular Gas

HH 211 jet

CO J=2–1
Low velocities

CO J=2–1
High velocities
SiO mm-wave rotational lines are an excellent tracer of jets: abundance enhanced by a few orders of magnitude in jets
HH 211 Lee et al. 2007

(a) IR ($\text{H}_2$+cont.)

(b) Cont.

(c) SiO(8−7)

(d) CO(3−2)
SiO HH 212 Codella et al. 2008
HH 212 Lee et al. 2007