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Last week: outflow-ISM interaction

Large-scale turbulence is likely driven by supernovae.

Smaller-scale turbulence can also be significantly driven by molecular outflows.

Outflows affect the envelopes of star-forming regions significantly. Early-on, they move large gas masses along with them. Later on, they evacuate the core, and the gas can only fall in perpendicular to the outflow.

The outflows cause shocks with high temperatures and pressures.

In these high-T and high-P regions, distinctively different chemical networks are observed compared to the unperturbed gas.

Chemical properties may be used for (relative) age dating.
Topics today

- Importance, difficulties, potentials & early observational claims

- Single-dish results at relatively low spatial resolution

- Interferometric high-spatial resolution observations and their implications

- Infall and outflow around ultracompact HII regions
**Importance of massive stars**

Great impact on ISM and star clusters, $L \propto M^3$

- Outflows and Jets
- UV-radiation
- Supernovae
- The majority of all stars form in clusters, massive stars exclusively.
- They produce all heavy elements
- Only star formation at high-Z that is observable.

**Problem:** With the typical accretion rates known from low-mass star formation, the radiation pressure of the forming massive stars would revert any infall for protostars $>10M_{\text{sun}}$. 

*Orion Nebula*

CISCO (J, K’ & H$_2$ (v=1-0 S(1))

Subaru Telescope, National Astronomical Observatory of Japan

January 28, 1999
Massive Star Formation

Modified classical scenario:
- Wolfire & Cassinelli 1987
- Jijina & Adams 1996
- Yorke & Sonnhalter 2002
- Norberg & Maeder 2002
- Krumholz et al. 2005, 2006
- Banerjee & Pudritz 2005

Coalescence and competitive accretion scenario:
- Stahler et al. 2000
- Bally & Zinnecker 2005

How to differentiate between both scenario?
- Molecular outflows and accretion disks
- Fragmentation and global collapse
- …
Results of early massive outflow research

Seem to be ubiquitous phenomena

Very massive and energetic

Seemingly less collimated than low-mass flows

Different entrainment scenarios proposed (deflection, winds...)

However, these results were based on small samples and poor angular resolution (between 21" and 60")

Shepherd et al. 1996a,b, Churchwell et al. 1997
Results of early massive outflow research

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Results of early massive outflow research seem to be ubiquitous phenomena. Very massive and energetic, seemingly less collimated than low-mass flows, different entrainment scenarios (deflection, winds...) were proposed. However, these results were based on small samples and poor angular resolution (between 21" and 60"").

Shepherd et al. 1996a,b, Churchwell et al. 1997

Model idea: Churchwell 1997
Plot: Arce et al. 2007
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Assuming momentum conservation:

\[ p_{\text{out}} = M_{\text{out}} v_{\text{out}} = M_{\text{jet}} v_{\text{jet}} = \frac{dM_{\text{jet}}}{dt} v_{\text{jet}} t = p_{\text{jet}} \quad \]

With a jet/outflow velocity ratio \( v_{\text{jet}} / v_{\text{out}} \sim 20 \) and a ratio of jet-flow rate to the accretion rate of \( \sim 0.3 \), one can estimate accretion rates:

\[ \rightarrow \text{Mean accretion rate} \ 10^{-4} \ M_{\odot}/\text{year} \]

high enough to overcome radiation pressure

Beuther et al. 2002
Outflow masses versus core masses

Accretion rate: \( \dot{M}_{\text{acc}} = f_{\text{acc}} \frac{M_{\text{core}}}{t_{\text{ff}}} \)

deflection efficiency: \( f_{r} = \frac{\dot{M}_{\text{jet}}}{\dot{M}_{\text{acc}}} \)

Multiply both equations and assume momentum conservation

\[ f_{r} f_{\text{acc}} = \frac{M_{\text{jet}}}{M_{\text{core}}} \left( \frac{v_{\text{out}}}{v_{\text{jet}}} \times \frac{M_{\text{out}}}{M_{\text{core}}} \right) = \text{constant} \]

\[ \Rightarrow M_{\text{jet}} = \text{constant} \times M_{\text{core}} \]

\( \dot{M}_{\text{acc}} \) is approximately a linear function of \( M_{\text{core}} \)
(assuming that free-fall time \( t_{\text{ff}} \) and \( f_{\text{acc}} \) are approximately constant)

Beuther et al. 2002
Accretion rates vs protostellar mass

$\dot{M} \propto M^{2.2}$

Infall and accretion rates overestimated?

Zhang 2005
Outflow properties

Mass

Mechanical Force

Outflow rate

Wu et al. 2004, 2005
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The pre-UCHII region IRAS05358+3543

$L_{\text{bol}} \sim 6.3 \times 10^3 L_{\text{sun}}$; no cm emission $\rightarrow$ pre-UCHII region

Beuther et al. 2002
Shocked $\text{H}_2$ emission in IRAS 18151-1208

$L_{\text{bol}} \sim 2 \times 10^4 L_{\text{sun}}$

no cm emission

$\rightarrow$ pre-UCHII region

Spectroscopy of the $\text{H}_2$ features reveals similar characteristics to low-mass outflows

$\text{Color: H}_2$

Contours: 875$\mu$m

Davis et al. 2004, Fallscheer et al. 2011
A young UCHII region: G192

Color contours: CO(1-0)
Inlay: mm continuum

\[ L_{\text{bol}} \sim 3 \times 10^3 L_{\odot} \]

Small UCHII at center
Collimation consistent with wind-blown bubble

Shepherd et al. 1998, 1999
Devine et al. 1999

[SII]
The UCHII region W75

Cluster of B0.5 to B2 stars associated with UCHIIs

$L_{\text{bol}} \sim 4 \times 10^4 L_{\odot}$

Wide-angle large-scale outflow, is that associated with the small-scale maser outflows?

Shepherd et al. 2003, 2004

Torrelles et al. 2003
In principle, all pv-diagrams appear reproducible via jet-entrainment and/or wide-angle winds, similar to the low-mass outflows.
Possible reasons: Stellar wind, magnetic diffusivity, (ionized) radiation?
An evolutionary scenario

Possible reasons: Stellar wind, magnetic diffusivity, (ionized) radiation?

Beuther & Shepherd 2005

Vaidya et al. 2011
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Rotation, Infall and Outflow motions

Beltran et al. 2006, 2007
The very luminous UCHII region G10.6-0.4

Keto 2002, 2005
Sollins et al. 2005

1.3cm continuum

Rotation/infall axis
Outflow axis

Infall in mol. and ionized gas.

Outflow in ionized gas perpendicular.

H66α recomb. line

H66α 1st moment

NH₃(3,3)
The very luminous UCHII region G10.6-0.4

Keto 2002, 2005
Sollins et al. 2005

Outflow in ionized gas perpendicular.
Massive molecular outflows are ubiquitous phenomena.

Jet-like outflows exists at least up to early-B and late-O-type stars.

Like in low-mass star formation, some outflows are likely driven by jet-entrainment whereas others are consistent with wide-angle winds.

Estimated accretion rates are high enough to overcome radiation pressure.

Flashlight effect additional helps reducing radiation pressure in equatorial plane.

Hence the observations support the scenario that massive star formation proceeds similarly to low-mass star formation.

The observations suggests an evolutionary sequence.
Outflows and Jets: Theory and Observations
Summer term 2011
Henrik Beuther & Christian Fendt

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