Shocks in Star Forming Regions

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Herbig-Haro Objects

- HH 1-2 discovered in the late 40s: L1641 (460pc) in Orion
- Studied in the optical: emission line spectra (Ha, SII, Ne)

Mid-70s: spectroscopy of HH objects are identified as shocks
- Proper motions: v ~ 100 km/s
- Highly-collimated jets associated with protostars
  from early Class 0 to Class II
  partly ionized material
Herbig-Haro Jets

HH 212
H₂

L1157
H₂

Cep E
H₂

IRAC 3 - 8µm

Zinnecker et al. (1998)
The Jet-Driven Bowshock Model

Observational confirmations:
HH 34 (Morse et al. (1992))
HH7 (Neufeld et al. 2009)

Raga & Cabrit (1993)

Velocity, $n_e$
Molecular Outflows

Outflows are ubiquitous: High-velocity features at small and large-scale (pc), shocks, cavities.

CO 2-1 emission at 10” resolution in TMC1

$Lefloch$ et al. (2011)

Bipolar structure
Cold gas (mm CO)

Tafalla $et$ $al.$ (2006)
Molecular Jets as Rosetta Stone

HH111 : Class I (25 L_⊙, 30 M_⊙) in L1617 (460 pc)
Optical jet : proper motions 300-600 km/s

Outflow : cold gas (15K) cavity dug out by the jet (bow)
Association with optical jet : momentum,
velocity distribution consistent with jet-driven bowshock

Molecular Jet : T > 300 K, v= 250-500 km/s

EHV Bullets : v= 250 km/s, T_{dyn} = 500 yr, T= 30 K,
M= 2x10^{-4} M_⊙

Association with optical jet : velocities, mass-loss rates
→ remnants of working surfaces

Cernicharo & Reipurth (1996)

Lefloch et al. (2007)
The current view on solar-type protostars

Protostellar envelope:
- Cold (10K), outer envelope: molecular depletion, superdeuteration
  Size: $10^4$ AU
- Warm (100K), inner envelope: hot corino: grain mantle sublimation, rich molecular complexity
  Size: 100 AU

Protostellar outflow
- High-velocity (100 km/s), highly-collimated ionic/atomic jet (1000 K)
  molecular jet
- Low-velocity (10 km/s), extended, molecular rich, outflow cavity (10K)
  Wide-angle wind?

Shocks in the envelope and the ambient cloud

Van Dishoeck et al. (2010)
What shocks can tell us

**Feedback processes in star forming clouds**
Triggered local star formation: shock compression

Gas acceleration: dispersal of gravitationally bound cores, turbulence injection

**The nature of the ejection mechanism: jet or wind?**
dynamics of the outflow cavity, mass-loss rate, etc... from shocked gas in cavity walls.

**Accretion-ejection mechanism**: MHD disk wind, X-wind, …

⇒ out of reach to ALMA!
Determining the origin of molecules in the jet allows to constrain the ejection mechanism.
⇒ Why are molecules more abundant in young protostellar outflows?

**Molecular complexity**: builds up during pre/protostellar phase:
which role for protostellar shocks through gas compression/heating, dust processing, UV radiation?
Shock Models

Two regimes of shocks (Draine, 1980)


Gas cooling in C-shocks dominated by CO, H$_2$, H$_2$O
Difficult from ground...

Dust grain processing: sputtering, etc...
→ Specific tracers to probe the shock structure

Cabrit et al. 2004

Flower & Pineau des Forets 2010
Shock Tracers

\[ \text{H}_2 \]

\[ \text{H}_2 \text{ excitation diagram} \]

\[ \text{C-shock} \]

\[ \text{J-shock} \]

\[ \text{MIR} \]

\[ \text{NIR} \]

\[ \text{SiO SED} \]

\[ \text{Schilke et al. (1997)} \]
H$_2$ Emission in HH2

**H$_2$ Spectroscopy** (Black & Dalgarno, 1976)

Simple rotator: Energy levels $E_J = hB(J+1)$
Homonuclear: no electric dipole transition

*Electric quadrupolar transitions*
$v=0$, $S(J) = J+2 \rightarrow J \ 28, 17, 12, 9.5 \mu m$
  First transition: $S(0) : J=2 \rightarrow J=0 : 514K$
  $A_{ij}$ are weak: optically thin emission

*Rovibrational transitions $(v,J)$ : 1-0 $S(1) \ 2.12 \mu m$

**H$_2$ excitation mechanisms** (Wolfire & Konigl, 1991)
  collisions: most commonly observed in molecular shocks
  fast shock: dissociative: X-ray, EUV
  Ly$\alpha$ / UV pumping: energetic, high-velocity ($v_\infty > 100 \text{ km/s}$), dissociative shocks

Spin: ortho-H$_2$ $(J=1,3,5,...)$ / para-H$_2$ $(J=0,2,4,...)$: no radiative connection
o/p H$_2$: typically $<< 1$ in clouds.
o/p conversion via chemical reactions (proton exchange)
H$_2$ Emission in HH2

Optical size ~ 2” (a few 10$^{16}$ cm)

ISOCAM observations (6”)
H$_2$ Emission in HH2

(Wolfire & Konigl, 1991; Black & van Dishoeck, 1987)

At LTE:

I ($j \rightarrow i$) = $N_j A_{ji} h \nu_{ji} / 4\pi$

$N_j / N = g_ig_s \exp(-E_j / k_b T) / Q(T)$

2 components

Warm, extended

T < 400 K, $N$(H$_2$) = 2x10$^{20}$ cm$^{-2}$   M = 2x10$^{-3}$ M$_\odot$

→ signature of the jet.

o/p = far from LTE

Hot, compact (2'')

T = 1000 K, $N$(H$_2$) = (2 – 16)x10$^{18}$ cm$^{-2}$

Comparison with shocks models:

(★) consistent with steady-state C-shock models and B close to equipartition:

$V_s = 30$ km/s   $n$(H$_2$) = 10$^4$ cm$^{-3}$   $ff = 0.07 : 1.6''$
H$_2$ Emission Properties

Warm shocked gas: 300-600 K  
C-shock: $V_s = 12-24$ km/s  
$n$(H$_2$) = $10^4$ cm$^{-3}$ ff = 10%

Hot shocked gas: 1000 – 1500K  
C-shock: $V_s = 36-50$ km/s  
$n$(H$_2$) = $10^4$ cm$^{-3}$ ff = 1%

Energy budget:  
$L$(H$_2$) = (0.25 – 0.5) $L_{\text{outflows}}$ (ISO)  

Impact on the Cloud  
Mass-loss rate:  
$M = (0.6-2.0) \times 10^{-6} M_\odot \text{ yr}^{-1}$

Core dispersal by outflows?  
(energetics, momentum)
Fit of $\text{H}_2$ mid- and NIR-data using a temperature stratification model: from 300 to 4000 K; otp ~ 1

Survey of protostellar shocks (Neufeld et al. 2009): $T^{-b}$: $T_{\text{min}} = 100$ K; $T_{\text{max}} = 4000$K
Non Steady-State Shocks

Cabrit et al. (2004)
Chemically Active Outflows
L1157

Spitzer 8 μm: grey and colorscale
CO: contours

Distance: 250 pc
Driven source: Class 0 protostar (IRAS20386+6751), $L = 4 - 11 L_\odot$;
Most chemically rich outflow known so far
Ideal laboratory to observe the effects of shocks on the gas chemistry
Shocks in L1157

Bachiller et al. (2001)

Gueth et al. (1996,98)
Complex Molecules in L1157

Rodriguez-Fernandez et al. in prep

Arce et al. 2008

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Large abundance of complex organic molecules: $X \sim 10^{-9}$ and rather low Tex

**Which formation mechanism?** Still strongly debated (depends on species)

Gas phase model: grain mantle evaporation of H$_2$O, H$_2$CO, CH$_3$OH, NH$_3$ followed by warm gas phase reactions: daughter molecules: HCOOCH$_3$, C$_2$H$_5$OH

Grain surface chemistry: complex molecules are formed on icy mantles and subsequently released.

In B1: n(H$_2$) high, T high... but

- the shock parameters are such that $t_{\text{cool}}$ (100 K) $< a$ few $10^3$ yrs $<<$ Timescale for gas phase models (Millar 1991).
- No efficient gas phase formation of HCOOCH$_3$ (Horn, 2004)

CH$_3$CN: see Bottinelli et al. (2007); low CH$_3$CN/CH$_3$OH wrt Hot Core Chemistry $\rightarrow$ gas phase formation (HCN, CH$_3$+).

Note: Max Col density is *not* at the apex but in the post-shocked gas.
Molecular abundances vary strongly between the flow and core, and between positions in the flow.

CO, HCO+: none
SO, CH$_3$OH: $x 10^3$
SiO: $x 10^4$

→ Grain processing: sputtering, mantle evaporation
Molecular Abundances

A simple pattern:
- small differences but for H$_2$CO and CH$_3$OH
- common chemistry and route formation

Tafalla et al. (2010)
SiO Emission in L1157

Good agreement between shock models and observations

Best modelling: CO, H$_2$, SiO
# The Promise of Herschel

<table>
<thead>
<tr>
<th></th>
<th>PACS</th>
<th>SPIRE</th>
<th>HIFI</th>
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<tbody>
<tr>
<td>Wavelength range</td>
<td>57-210(\mu m)</td>
<td>194-672(\mu m)</td>
<td>157-213 and 240-625(\mu m) (with gap)</td>
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<tr>
<td>Field of view</td>
<td>47(\times)47(\prime)</td>
<td>2.0(\prime) (unvignetted)</td>
<td>Single pixel (see below)</td>
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<tr>
<td>Pixel size</td>
<td>9(\prime)</td>
<td>16(\prime), 34(\prime)</td>
<td>39(\prime) (488GHz), 13(\prime) (1408GHz)</td>
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<tr>
<td>Sensitivity (5(\sigma)/1hr, point source)</td>
<td>2(\times)10(^{-18}) Wm(^{-2}) (130(\mu m), 1st order), 5(\times)10(^{-18}) (70(\mu m), 3rd order), Continuum 0.2Jy (130(\mu m))</td>
<td>2.8(\times)10(^{-17}) Wm(^{-2}) (250(\mu m), low resolution), 3.3(\times)10(^{-17}) Wm(^{-2}) (500(\mu m), low resolution)</td>
<td>TBD (see below)</td>
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<tr>
<td>Resolution</td>
<td>1500-2000</td>
<td>40-1000</td>
<td>1000-10(^{5})</td>
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The Promise of Herschel

1: To get a full description of the shock dynamics ($B$, $n(H_2)$, $T_k$, $V_s$) from high-J CO, H$_2$O lines with a resolution similar to largest ground-based telescopes.

2: To explore the molecular complexity in protostellar outflows/shocks: Hydrides, CS, HCO$^+$, HCN, CH$_3$OH, H$_2$CO...

3: To establish the link between the cold gas (mm) and hot gas (IR).
L1157-B1 as seen with Herschel

**HIFI** : 490 – 1900 GHz. 27 hrs.
- Band 1a-1b covered in an unbiased way
- Selected bands of 20 GHz
- Deep integrations on “key” lines (H$_2$O, OH, C$^+$, …)
Spectral resolution : 0.5 MHz

**PACS** : 1428 – 5455 GHz (55 – 200 μm). 5hrs. In spectroscopic mode, PACS images a field of ~ 50 x 50 arcsec, resolved into 5 x 5 pixels (size = 9.4”).

**SPIRE** : maps the emission in the range 450 -1540 GHz at positions separated by 2 beams (from 80” to 30”)

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Spectrum 55 – 672 µm
CO up to $J_{up} = 24$, (o/p) H$_2$O, OI

Energy Budget
L(H$_2$O) $\sim$ 0.10 – 0.20 L(CO)
L(H$_2$) = 0.40 L$_{\text{shock}}$
Gas cooling dominated by H$_2$ and CO…
In agreement with WISH (van Dishoeck et al. 2011)
Species detected

- CO, $^{13}$CO, C$^{18}$O, CI, HCO$^+$
- H$_2$O, OH, OI
- H$_2$CO, CH$_3$OH
- NH$_3$, NH, HCN, HCl, H$_2$S, CS, ...

Different velocity regimes

- LVC : « Warm »
  -7 < v < +4 km/s
- HVC : « Hot »
  -30 < v < -7 km/s

Molecular rich

- CO, H$_2$O, SiO
Origin of the Emission

High-Velocity Component: compact: ~ 7”

Low-Velocity Component: Extended ~ 15-20”

CO 6-5 @ CSO

SiO 2-1 @ PdBI
The High-Velocity Gas

Excellent match in the HVC for all shock tracers: CO, H$_2$O, SiO
Excellent match between profiles of high-excitation lines: SiO 8-7 (75K), CO 16-15 (752K), H$_2$O $3_{12}$-$3_{03}$ (215 K)

The high-J CO lines are tracing a compact, hot gas component, well detected in the HVC

Hot component peaks 5” North of B1
It is slightly elongated towards B1.
Compact size: 7”

Similar to SiO 2-1 HVC map of PdBI

Benedettini et al. (2011)
A Simple Model of the Hot Gas Emission

**Step 1:** Physical conditions from PACS CO lines:

- $400 \, \text{K} < T < 1000 \, \text{K}$
- $n(\text{H}_2)$: a few $10^4 - 10^5 \, \text{cm}^{-3}$

**Step 2:** CO line emission from the hot component in the HIFI bands:

- Adopting same line profile as CO 16-15
- Lower-T solutions are favored by SED:
  - $T = 500 \, \text{K}$
  - $n(\text{H}_2) = 10^5 \, \text{cm}^{-3}$
  - $N(\text{CO}) = 8 \times 10^{15} \, \text{cm}^{-2}$

The ortho-water line spectrum can be approximately accounted for the same set of physical conditions with $N(\text{o-H}_2\text{O}) = 7 \times 10^{15} \, \text{cm}^{-2}$ and size of 10’’

$$N(\text{H}_2\text{O}) / N(\text{CO}) \sim 1$$
Comparison with Shock Models

Line emission in the range PACS – HIFI of the hot component can be accounted for by a J-type shock into pre-shock gas of density $n(H_2) = 2 \times 10^4$ cm$^{-3}$.

Dissociative J-type shock with $V_s > 30$ km/s?

HIFI CO line residuals: consistent with a C-type shock component $V_s = 20$ km/s into pre-shock gas density $n(H_2) = 2 \times 10^4$ cm$^{-3}$.

(Flower & Pineau des Forets 2010; Cabrit et al. 2011)
The Low-Velocity Component

CS : up to $J_{\text{up}} = 12$
HCN : up to $J_{\text{up}} = 7$

Simple (LVG) modelling: slab of gas at 1 temperature

Size $\approx 20''$
n(H$_2$) $\approx (1-2) \times 10^5$ cm$^{-3}$
$T = 100-150$ K

LVG modelling of CO line emission:
$N(\text{CO}) = 3 \times 10^{17}$ cm$^{-2}$
n(H$_2$) = $2 \times 10^5$ cm$^{-3}$
$T = 130$ K

LVG modelling of H$_2$O
$N(\text{H}_2\text{O}) \sim 10^{16}$ cm$^{-2}$ : $N(\text{H}_2\text{O}) / N(\text{CO}) \sim 0.03$
A secondary peak occurs between -3.0 and -4.0 km/s (here defined medium velocity, MV) and well outlined by e.g. HCN(7-6). The MV peak is visible also in NH$_3$ and in some lines of CH$_3$OH and H$_2$CO.

PdBI: the MV secondary peak is observed in a couple of lines of CH$_3$OH at 3mm and only towards the western B1b clump → a velocity component mainly coming from the western side of B1, while the HV gas is emitted from the eastern one.
Molecular Complexity in the LVC

**NH$_3$/H$_2$O decreases as a function of velocity**

Different pre-shock ice compositions in the MV gas?

Different formation mechanisms:
- NH$_3$ is released by grain mantles
- H$_2$O water is released by grain mantles + high-T reactions in the warm shocked gas

NH$_3$/H$_2$O trend reflects the destruction of NH$_3$ in the shock (Viti et al. 2011).

NH$_3$ is initially frozen onto dust grains, released in gas phase when passing through the shock. For $T_{\text{kin}} > 3500$K,

$$\text{H} + \text{NH}_3 \rightarrow \text{NH}_2 + \text{H}_2 \quad (E_{\text{act}} = 5000$K)$

Condition $T_{\text{max}} > 4000$K is met for typical shock parameters:
- $n(\text{H}_2) = 5 \times 10^4 \text{ cm}^{-3}$, $V_s = 40$ km/s

→ Search for NH$_2$, NH: marginal detections

Codella et al. (2010)
Water emission in L1157

Strong water emission from the embedded protostar and the CO peaks of the outflow

Emission peaks trace the shock interaction regions: H$_2$O follows SiO

Nisini et al. (2010)

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Water in Outflows
Water Observations from Ground

Thermal water lines cannot be observed from ground.

**Masing water lines**

o-H\(_2\)O \(6_{16} - 5_{23}\) 22.23GHz \(E_{up} = 609\) K

survey Nobeyama 45m and VLA (Furuya et al., 2003)

173 ysos : 39 sources detected

Good correlation \(L(H_2O) - L(\text{free-free 6cm})\) : continuum free-free arises from ionised material produced by shock with neutral jets. Emission from inner 100 AU : arcsec/subarcsec size.

**Information at large scale with good angular resolution (20") : IRAM, CSO**

p-H\(_2\)O \(5_{15} - 4_{22}\) 325.5 GHz \(E_{up} = 475\) K : CSO

p-H\(_2\)O \(3_{13} - 2_{20}\) 183.3 GHz \(E_{up} = 205\) K
Water Emission in Orion

Extended $\text{H}_2\text{O}$ emission
CSO 325 GHz : 24”
IRAM 183 GHz : 18”

Emission : IRc2, outflow, ridge

$\text{H}_2\text{O}$ abundance : $x = 10^{-4}$ Plateau
$x = 10^{-6}$ ridge

Shocked Water Emission in CepE

H₂O 183 GHz
-110 ; +70 km/s

N(H₂O) = (1.0 - 8.0) x 10^{17} cm²⁻¹
X(H₂O) = (0.5 - 3.2) x 10⁻⁴

Lefloch et al 2011
Shocked Water Emission in CepE

Similarity of H$_2$O and SiO profile!

Origin: small clumps (1’’x2’’) in the jet

Physical conditions from SiO analysis

- $n$(H$_2$) = $10^6$ cm$^{-3}$
- $T = 200$ K

$Lefloch$ et al 2011

N(H$_2$O) = (1.0-8.0)$\times$ 10$^{17}$ cm$^{-2}$
X(H$_2$O) = (0.5-3.2)$\times$ 10$^{-4}$
Until Herschel, « high » angular resolution observations came from maser observations H$_2$O 22/ 183 GHz : only few sources detected; masers are time variable.

ISO detected strong H$_2$O emission in Class 0 protostars :
→ passively heated envelope or shocked outflow material ?
→ What is the role of the outflow cavity?

do outflow shocks contribute to the molecular complexity of hot corinos ?
Early Herschel results

$H_2O \, J_{10-10} \, @ \, 557 \, GHz$

- Envelope emission expected to be $< 5 \, km/s$...
- Emission outflow dominated, even in small beam (2000 AU)
- Ground-state $H_2^{18}O$ broad (Lefloch et al. 2010; Kristensen et al. 2010; Kristensen et al. in prep.)

Velocity scale: -100 to 100 km/s
Water bullets in a low-mass protostar

LI448:
D ~ 250 pc
L ~ 11 L☉

Absorption to continuum
Broad outflow
Molecular bullets

Bullets H₂O rich indicating fast and efficient formation from atomic gas

Kristensen et al. (2011; astro-ph)
Inner region

- 5h integration on excited $\text{H}_2^{18}\text{O}$ line
  ($\text{H}_2^{18}\text{O} \, 3_{12}-3_{03} \, @ \, 1094 \, \text{GHz}$)
- FWHM $\sim 5 \, \text{km/s}$
- **Direct** detection of inner region with single-dish telescope
  (Visser et al. in prep.)

$E_{\text{up}}/k_B = 250 \, \text{K}$

N1333-I2A
D $\sim 235 \, \text{pc}$
L $\sim 20 \, \text{L}_\odot$
Protostellar Jets

Knotty structure = internal shocks

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Good agreement numerical simulations - observations
A Different Molecular Composition

Composition of protostellar jets is much more simple, and very different from outflow wings and protostellar envelopes: CO, SiO, SO, HCO+, HCN, H₂CO, H₂O
C-poor /O-rich with respect to outflow wings: shocks in ambient gas.

Differences between sources are observed: HCN/CH₃OH
Still not understood.

Peculiar chemistry
How do jets form and why are molecules so abundant in Class 0 jets?
Several scenarios: wide-angle wind (Glassgold, 1991)
MHD disk winds (Panoglou, 2009): time dependence!
reformation in internal shocks

Observational tests from abundance ratios (CO, H₂O, SiO).
First Conclusions

Protostellar shocks shine!

Protostellar shocks enhance the molecular complexity of the parental cloud from simple to heavy organic molecules: the census remains to be done.

Herschel permits to constrain the thermal structure of shocks, which models succeed partly to explain:
- CO and H\textsubscript{2} appear to dominate the gas cooling in protostellar shocks
- H\textsubscript{2}O appears to probe the same regions of shocks as other tracers: CO, SiO
- H\textsubscript{2}O production is dominated by high-T reactions in shocks → contribution of shocks to molecular complexity in protostellar cores/corinos.

Several hydrides are detected in shock regions: NH, HCl and bring constraints on shock properties from appearance/disappearance in gas phase.

Interpretation relies on close coupling observations/models: progress on shock models (collisional coefficients)

Exploration of the inner protostellar region begins:
- chemistry in jet yields provides good tests on jet launch region.
- models are needed
Thanks to all my collaborators of the CHESS and WISH teams!