Kinematics of the shocked molecular clumps of SNR IC 443

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21cm image: Lee et al. (2012)
Background: SNRs interacting with MCs

- Broad molecular line profiles
- Large line ratio ($R_{21/10} > 1$)
- 1720MHz OH maser ($n \approx 10^5$ cm$^{-3}$, $T = 50$ - 125 K)
- IR emission lines [FeII] and H$_2$
- Analogue shock conditions in ULIRGs

Su et al. (2014)
Lee et al. (2012)
JCMT HARP CO (3-2) observations
Large-scale kinematics

- A global collective expansion velocity of 25 km s\(^{-1}\) within the hot, fully ionized SNR interior.

Van Dishoeck et al. (1993)
Clump B

- 3 sub-clumps resolved
- High velocity up to -95 km s\(^{-1}\) in the western region
Clump C and C0

- gas patches C1, C2, C3 discriminated at -17 km s\(^{-1}\)
  shock layers at inner and outer side of the clump (Wang & Scoville 1992)
- 4 knots resolved in the flow ablating from the small cloud SC 05
Clump D

- Clumpy gas patches and filaments show that the fragmentation is happening.
- The shock has propagated towards the outer rim at SC 06.
Clump E

• 3 main velocity components:
  – More negative gas patch concentrated in the south at -7 km s\(^{-1}\)
  – Central patches, with SC 07 & 08 being impacted by the SNR shock
  – Knots with redshift velocity in the west
Clump F

- At least 3 sub-clumps resolved, $R_{32/21} \sim 1$
- A weak arc structure, collecting effect of the progenitor’s stellar wind
Clump G1

- Almost totally self-absorption by the foreground preshocked gas
- Composed of 2 sub-structures
Clump G2

- Five sub-clumps, quasi-regular spacing of 0.31-0.47 pc
- the progenitor’s stellar wind sweeping by the foreground molecular gas, and self-collapsed
Comparison with the 2MASS K band Emission

- Hot $\text{H}_2$ gas $v = 1 - 0 \ S(1)$ (T>2000 K)

- good morphology correlation

- A combination of J- and C- type shock (Snell et al. 2005, Neufeld et al. 2007)

- Clump B & F:
  - weak in central cores, lower T
    -> slow C-type shock with low fractional ionization
  - peak in western diffuse clump
    -> J-type shock
Turbulence in the subclumps

- **Diffuse component at -40 km s\(^{-1}\)**
  -> shock propagates into a low-density interclump media

- **Turbulence with a velocity gradient of \(dV/dR \approx 30 \text{ km s}^{-1} \text{ pc}^{-1}\)**
  Similar order as in distant ULIRGs (Arp 220), power injection via SNRs dominated, decoupling of gas and dust \((T_{\text{kin}} > T_{\text{d}})\)

- **Dissipated at a crossing timescale of**
  \(t_{\text{cr}} \approx (l/\delta v) \approx 10^5 \text{ yr}\)
Fragmentation of Molecular Clumps

- **crushing time of shocked dense cloud:**
  \[ t_{cc} = \chi^{1/2} r_0/v_i \sim 1 \times 10^5/(v_i/100 \text{ km s}^{-1}) \text{ yr} \]

- Assume Isothermal and thermally supported
  - Critical mass per unit length
    \[ M/R = 16-48 \text{ M}_\odot \text{ pc}^{-1} (T=10-20 \text{ K}) \]

- Fastest-growing unstable mode of the fluid instability
  - characteristic spacing of 0.6pc
Summary

• Rich substructure and the kinematics at smaller scales of the shocked molecular gas are resolved in CO (3-2).
• The sub-clumps in B and F clumps are likely fragmented dense cores under a slow C-type shock, having a turbulent with dV/dR of 30 km s\(^{-1}\) pc\(^{-1}\).
• The weak diffuse gas at -40 km s\(^{-1}\) traces a relatively low-density interclump media associated with B sub-clumps.
• The fibrous G2 clump show five fragmented sub-clumps. It’s probably formed by the progenitor’s stellar wind sweeping by the preshock gas and then self-collapsed by cylinder collapse.

Thank you!