ALMA Observations of the Ultra-Broad-Velocity-Width Molecular Feature "Bullet" in the W44 Supernova Remnant

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Background

W44

- Supernova remnant located in the direction of Aquila
- Distance: ~3 kpc (Caswell et al. 1975)
- Contains a pulsar (PSR B1853+01) inside (Wolszczan et al. 1991)
- A giant molecular cloud is associated with the radio shell (Seta et al. 1998)
- Supernova energy input to the molecular cloud: (1–3) × 10^{50} erg (Sashida et al. 2013)

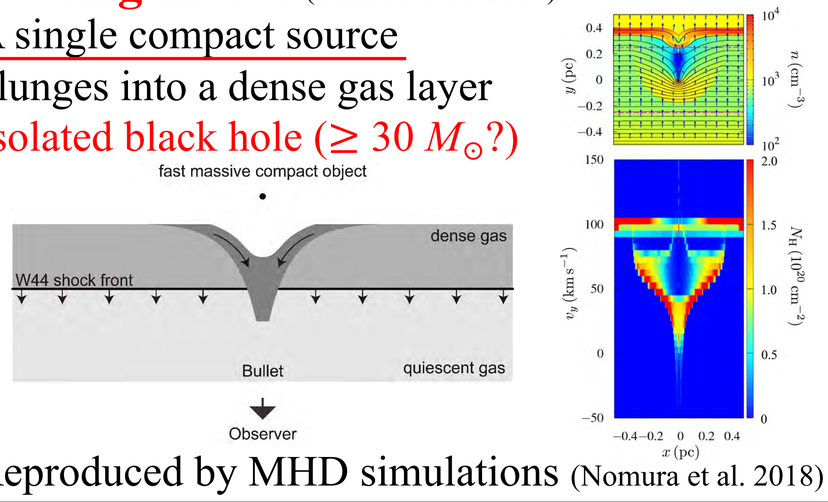
Locally energy imparted to the Bullet region : $10^{46.3–46.8}$ erg

Bullet

- Ultra-high-velocity cloud associated with W44
  - Compact size: 0.5 × 0.8 pc^2
  - Extremely broad velocity width: ~120 km s^{-1}
  - Enormous kinetic energy: 10^{48} erg
- "Y"-shaped position–velocity structure
- No counterparts at other wavelengths

Shooting model (Yamada et al. 2017)

- A single compact source plunges into a dense gas layer
- ➡ isolated black hole (≥ 30 $M_\odot$?)



- Reproduced by MHD simulations (Nomura et al. 2018)

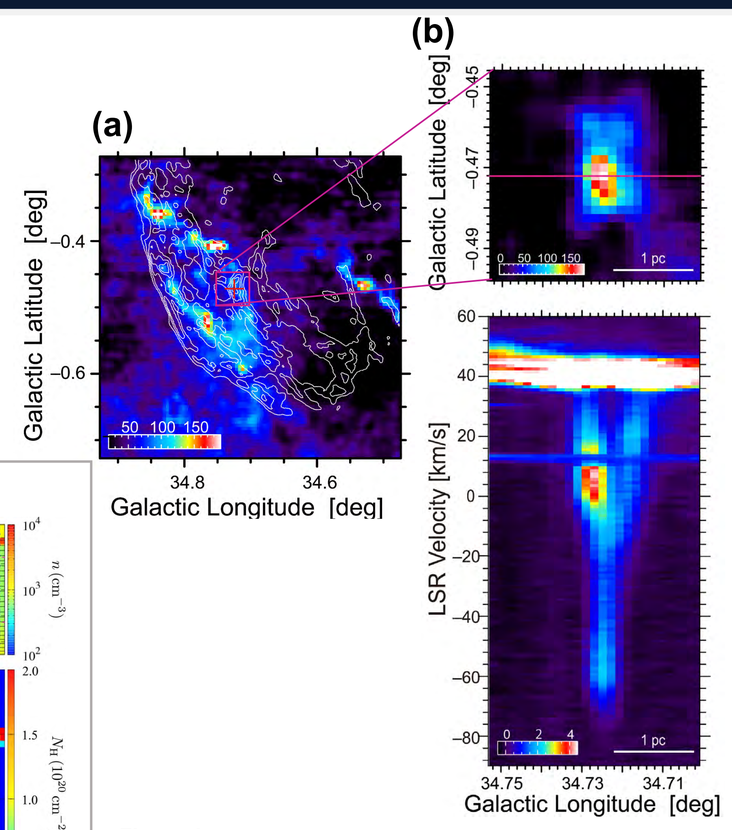


Figure 1.
a. Integrated CO *J* = 3–2 map toward W44 (Sashida et al. 2013). Contours represent 1465 MHz continuum emission (Jones et al. 1993).
b. Top: Integrated CO *J* = 3–2 map of the Bullet
Bottom: Longitude–velocity map at *b* = 0.472°, reproduced from Yamada et al. (2017).

Objectives

- Reveal the detailed structure of the Bullet
- Test the shooting model proposed by Yamada et al. (2017)

Observations & Analysis

Atacama Large Millimeter/submillimeter Array (ALMA)

- Line: CO *J* = 3–2 (345.79 GHz)
- Period: Mar 23–24 and Apr 16–17, 2017

Analysis Method

1. Imaging of interferometric data
   - Extraction of line components
   - Deconvolution using CLEAN
2. Combination with single-dish data



➡ Reveals detailed spatial–velocity structure of the Bullet
Resolution: 1.6″ × 1.2″ (0.023 × 0.018 pc^2)

Results

- Detection of the Bullet's Y-shaped structure "Bullet Main"
  - Extends ~0.4 pc at the negative-velocity end
  - Asymmetry implies an oblique plunge
- Newly detected eight V-shaped components "Petit–Bullets (PBs)"
  - More compact than Bullet Main: ~0.1–0.3 pc
  - Broad velocity width: ~72–162 km s^{-1}

➡ **Each may be formed by plunges of point-like gravitational sources**

Figure 2.
a. Integrated CO *J* = 3–2 map of the Bullet. Black crosses mark the positions of the PBs.
b. Longitude–velocity map at *b* = 0.4710°.
c. Latitude–velocity map at *l* = 34.7161°.

Discussion

Nature of the plunging object

- No bright counterpart → not a massive star
- High velocity opposite to Galactic rotation → likely a halo object
- Forms Bullet Main and 8 Petit–Bullets → not a single source

Mass of the Bullet Main's plunging object

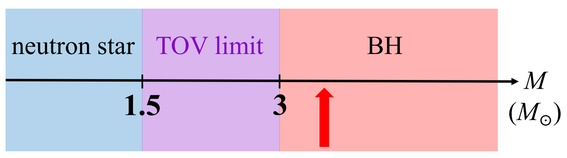
$$M_* V_* \gg M_{\rm gas} V_{\rm Bullet} \sim \frac{1}{2} M_{\rm gas} V_*$$

➡ $M_* > 3.67\ M_\odot$
Clearly exceeds the TOV limit !

Table 1. Physical Parameters

Parameters	Quantity
Size (S)	0.301 pc
Gass Mass ($M_{\rm gas}$)	7.33 $M_\odot$
Kinetic Energy ($E_{\rm kin}$)	$10^{47.2}$ erg

➡ **BH is a likely accelerator**

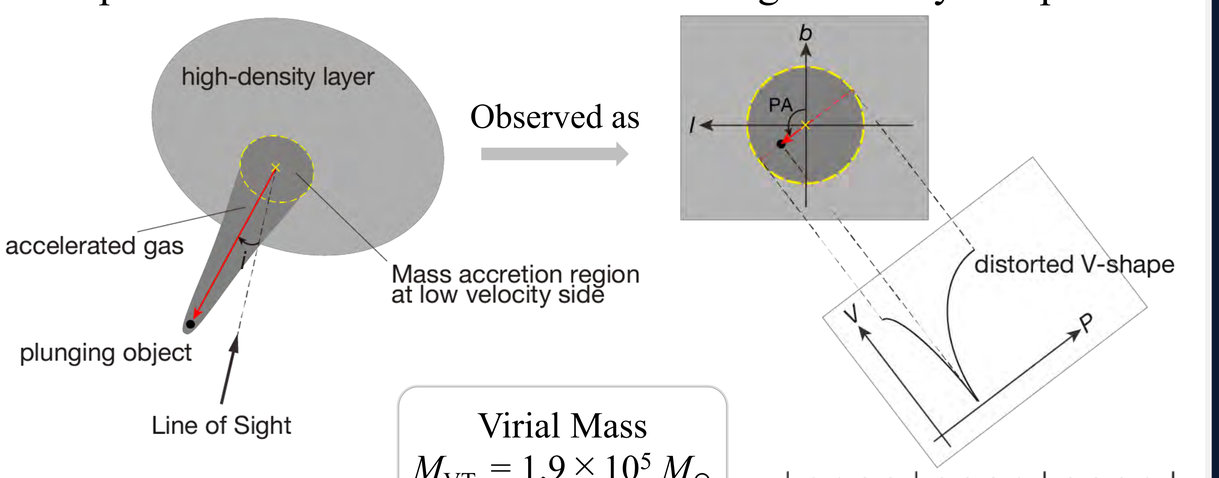


Future Work

- ALMA observations with dense tracers (e.g., HCO^+) refine the velocity vectors and reveal internal structures
- Deep NIR imaging with Subaru/MOIRCS to search for stellar counterparts to Petit–Bullets

Determination of Velocity Vector

- Use positional offsets between low- and high-velocity components



Virial Mass
$M_{\rm VT} = 1.9 \times 10^5\ M_\odot$

Averages	Dispersions
$V_l = 0.8$ km s^{-1}	$\sigma_{V_l} = 10.4$ km s^{-1}
$V_b = -0.6$ km s^{-1}	$\sigma_{V_b} = 12.4$ km s^{-1}
$V_{\rm LSR} = -64$ km s^{-1}	$\sigma_{V_{\rm LSR}} = 27$ km s^{-1}

➡ Possibly a self-gravitating system with systematic and random motions

➡ **Maybe a globular cluster in the Galactic halo?**

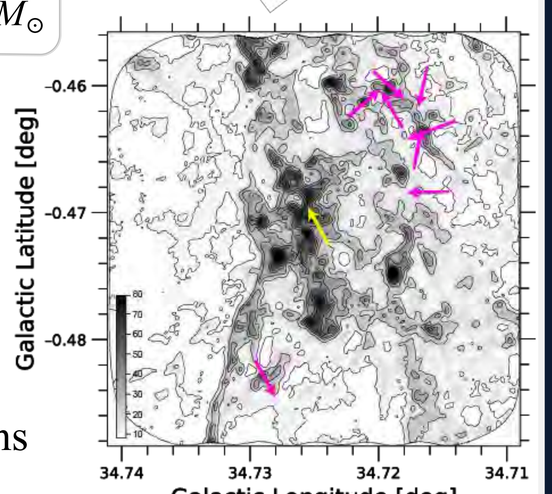


Figure 3. Integrated CO *J* = 3–2 map of the Bullet. Magenta arrows show velocity vectors of the Bullet Main and Petit–Bullets (scale arbitrary).