Star-Forming Hot Bubbles in Irregular Galaxies

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5. Summary

1. Concept

Bubble & Superbubble (1/7)

- **Massive stars**
  - Stellar wind and supernova explosion create shells and cavities which impact on the surrounding ISM (A. *Camps-Farina et al. 2017).*
- **Bubble**
  - Bubbles blown by massive stars may contain shocked fast winds at temperature $\geq 10^6$ K which emits diffuse X-rays (*Chu et al. 2006).*
  - Bubbles and superbubbles have been well detected in the Galaxy and in nearby galaxies via Hα and H I 21-cm line (A. *Camps-Farina et al. 2017).*
  - Bubbles and superbubbles share a similar structure: a swept-up dense shell with an interior filled by low-density hot gas *(Y. –H. Chu 2007).*

Bubble & Superbubble (2/7)

	Supergiant shells (SGSs)	**Superbubbles**	**Bubbles**
Sizes (pc)	~ 10^3	~ 10^2	~ 10
Dynamic ages (yr)	~ 10^7	~ 10^6	
Star formation	Multiple generations or episodes	One episode	

- **Superbubble**: kiloparsec scale, by starbursts, fast stellar winds, supernova explosions from groups of massive stars.
- **Bubble**: a few parsec, by fast stellar winds from individual massive stars.

(Y. –H. Chu 2007)

Bubble & Superbubble: Supernova Remnant (3/7)

- **General examples**
  - The Large Magellanic cloud superbubbles by supernova and stellar wind *(Ambrocio-Cruz et al. 2016; Reyes-Iturbide et al. 2014)*

SNR 0509-67.5 is a **supernova remnant** located in the Large Magellanic Cloud.

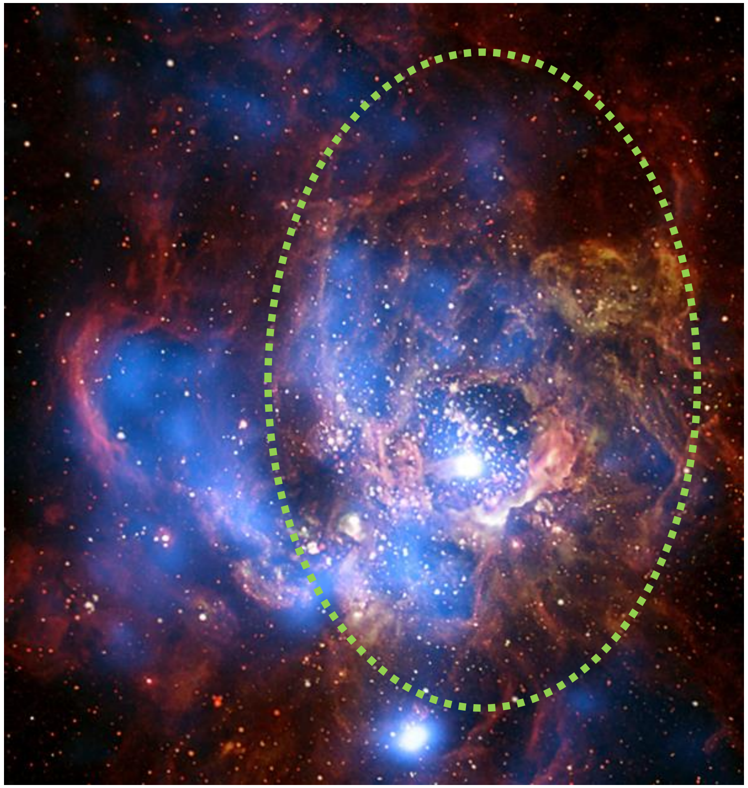
A new composite includes a Hubble image of the **star field** and **gas** that has been shocked by the expanding blast wave (pink).

Chandra data (blue and green) show **material in the center of the remnant.**

(http://www.chandra.harvard.edu/photo/2010/snr0509/)

Bubble & Superbubble: Stellar wind (4/7)

- **General examples**
  - NGC 604: The largest region of star formation in the nearby galaxy M33.

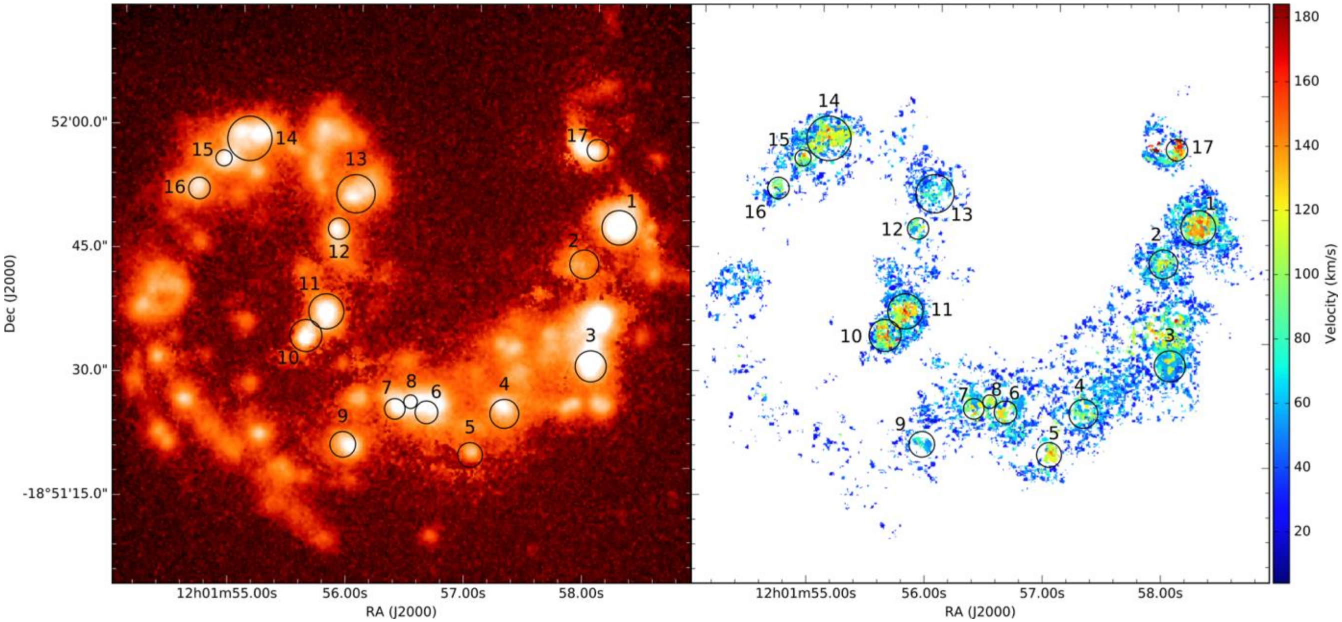


This composite image from Chandra X-ray data (colored blue) and optical light data from the Hubble (red, green and yellow): 200 hot, young, massive stars reside.

Bubbles in the cooler gas and dust have been generated by **powerful stellar winds**, which are then filled with hot, X-ray emitting gas. *(http://chandra.harvard.edu/photo/2009/n604/n604_hand.html)*

Bubble & Superbubble: Supernova Remnant (5/7)

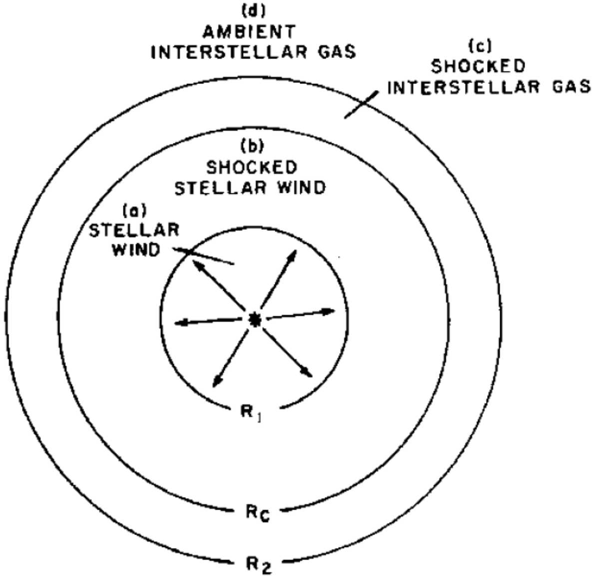
- **General examples**
  - Arp 244 (NGC 4038/9, Antennae) (A. *Camps-Farina et al. 2017*).



Left: Hα intensity map, Right: expansion map for the Antennae galaxies.
Circles: superbubble (~150 and 500 pc in radius).
The superbubbles clearly appear around most of the brightest regions.

Bubble & Superbubble (6/7)

- **Various models**
  - Weaver et al. 1977 model has formed the basis of bubble models with more complex conditions in the ambient medium and time-dependent stellar winds.
  - Freyer et al. 2003, 2006 models by adding radiation effect: Photoionization significantly influence the morphological evolution of interstellar bubbles formed during the main sequence stage.
  - Superbubbles modeled with the consideration of interstellar density gradient out of the galactic plane can produce blowouts into the galactic halo *(Mac Low et al. 1989).* The expansion and blowout of a superbubble can be impeded in the direction perpendicular to the magnetic field of the ISM *(Tomisaka 1992).*



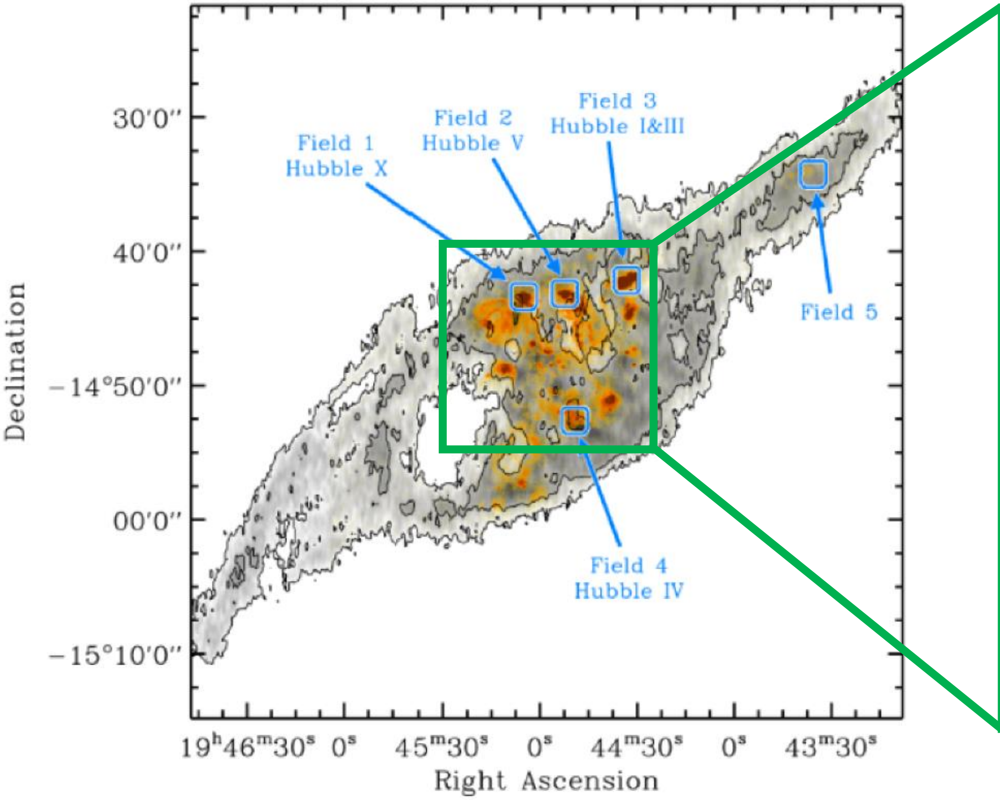
Structure of interstellar bubble.
(Weaver et al. 1977)

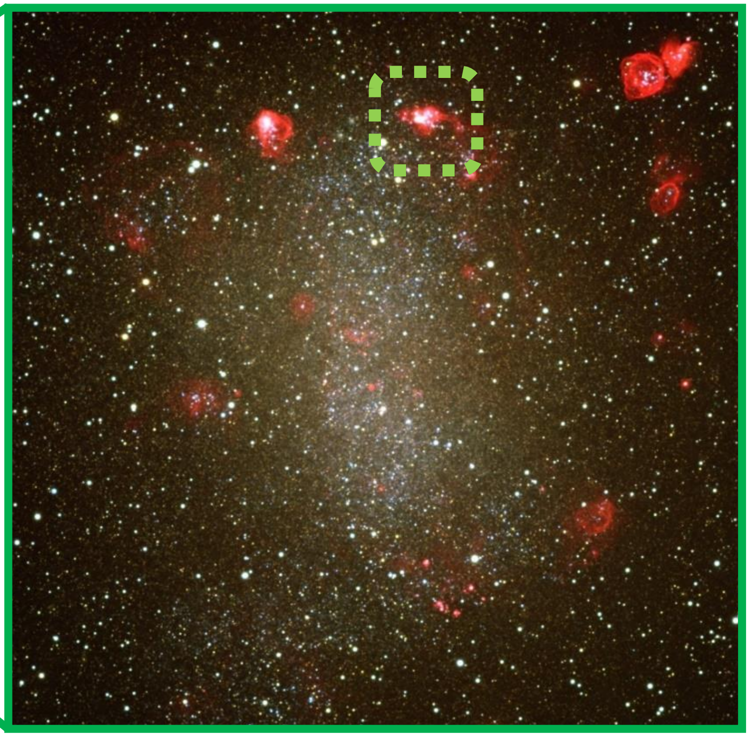
Bubble & Superbubble (7/7)

- **Various models**
  - Segura et al. (1996a, b) considered mass-loss rates and stellar wind velocities that varies along stellar evolution: modeled the development of interstellar bubble during the main sequence and circumstellar bubble during the WR (Wolf-Rayet (WR) stars *(Wrigge et al. 2005*)). Instabilities in the dense swept-up circumstellar bubbles shells cause fragmentation and clumpy morphologies.
- **Noticeable example** (*Chu et al. 2006)*
  - S 308: a circumstellar bubble in an early evolution stage with hot gas.
  - NGC 6888: swept-up supergiant wind fragments and breaks out into the shell, a later evolutionary stage than S 308.
- **NGC 6822 Hubble V**: We suggest as new example of hot bubble with clumpy molecular structure.

2. NGC6822 Hubble V

NGC 6822 Hubble V





NGC6822 from NOAO by B, V, Ha

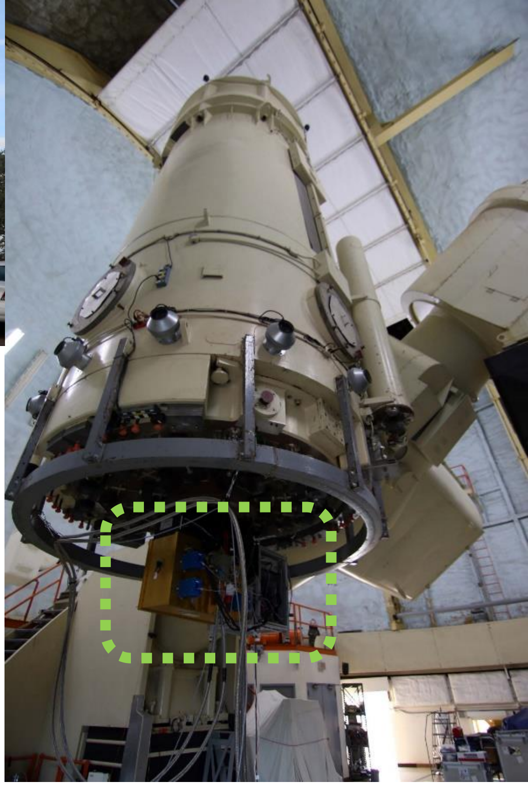
Left: ALMA survey fields (blue rectangles, each 250 pc x 250 pc in size) **overlaid** on an **H I image (grayscale)** with contours and an **Hα image (orange color) highlighting** the location of prominent **H II regions**. *(Schruba et al. 2017)*

NGC 6822 Hubble V

- **NGC6822**
  - Local Group.
  - Metal-poor (20% of the Galactic values) dwarf irregular galaxy.
  - D = 474 $\pm$ 13 kpc. *(Rich et al. 2014)*
  - $M_{Total} = 1.5 \times 10^9 M_\odot$, Age ~4 Myr
  - Bar dominated by an irregular distribution of OB associations and H II region. *(Israel 1997)*
- **NGC6822 Hubble V**
  - One of the brightest H II region complex (another: Hubble X)
  - OB association: called OB 8 by Hodge 1980 or OB 3 by Wilson 1992a, 80 stars brighter than $m_{NUV} < 22.5$ mag, high temperature, massive star candidates.
  (Bianchi & Efremova 2006) (Schruba et al. 2017)

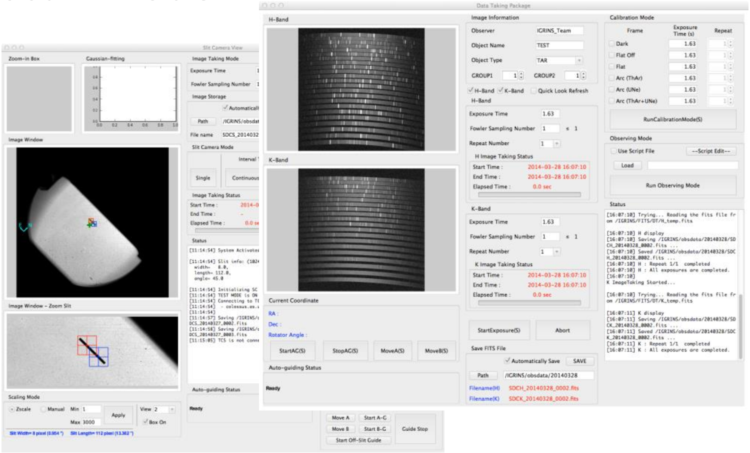
3. IGRINS Observation

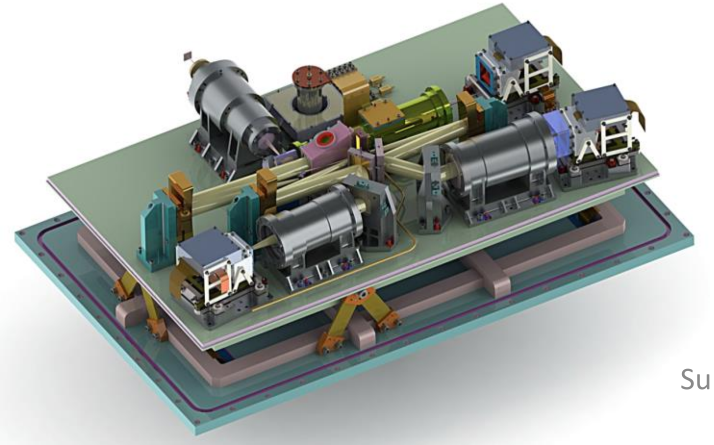
IGRINS Observation



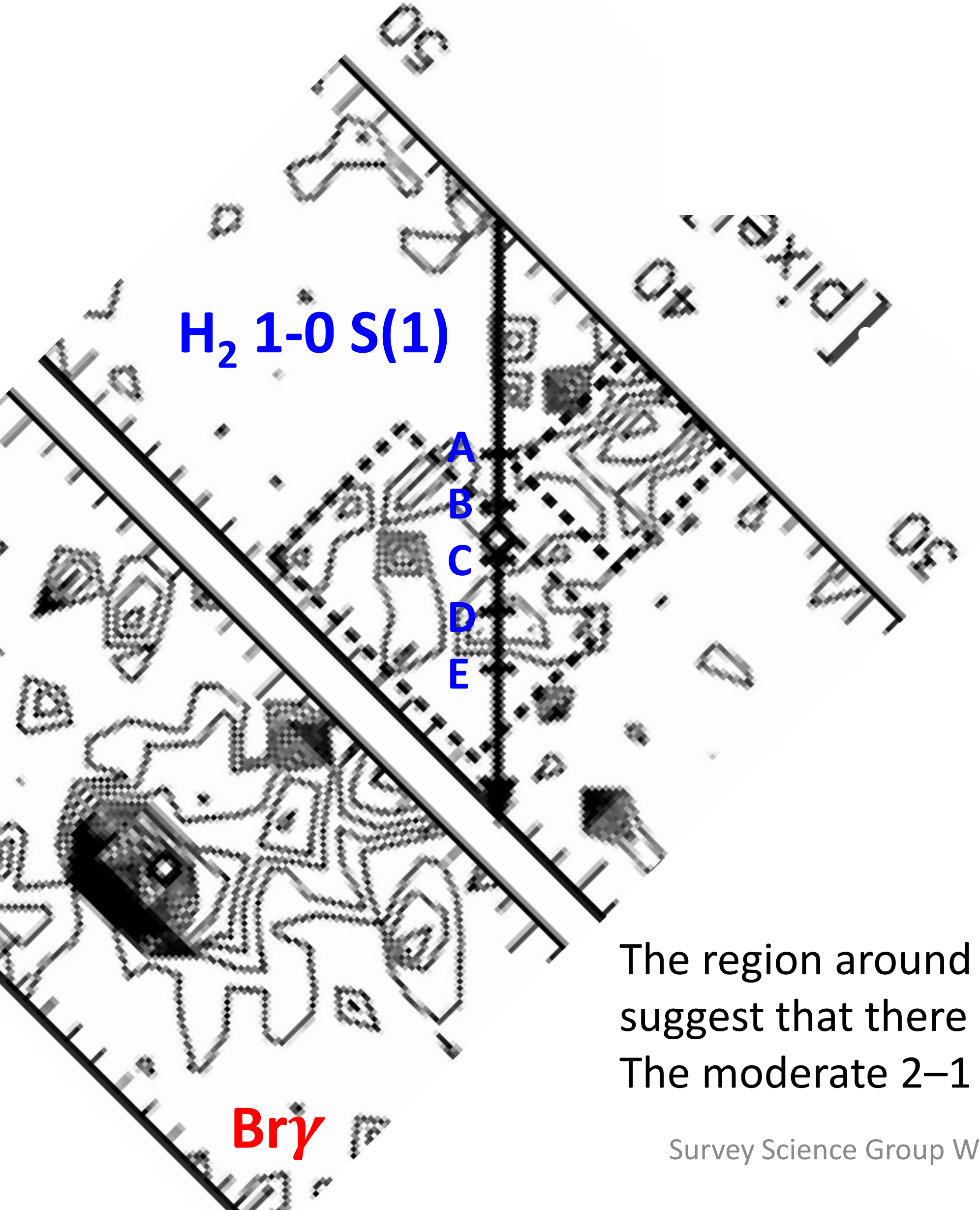
Line	Wavelength
Brγ	2.1661 µm
H_2 1-0 S(1)	2.1218 µm
H_2 2-1 S(1)	2.2477 µm
H_2 1-0 S(0)	2.2227 µm
HeI	2.0587 µm

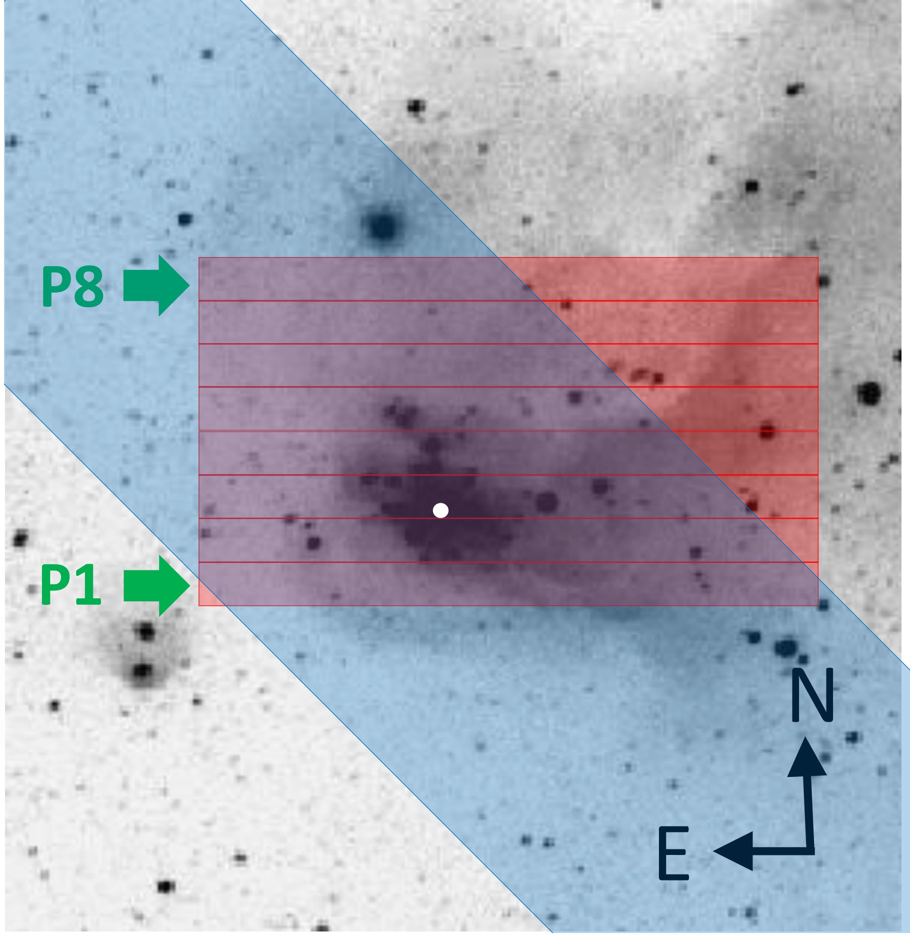
- IGRINS (R = 45,000) attached on the 2.7m telescope at the McDonald Observatory in Texas, US in May and July 2014, 2016.
- Slit (1 x 15 arcsec) scanned regions of 15“ x 8” on H and K bands used by Slit scan Mode.





Observation





HST image and IGRINS 8 Slits (Red).
NE long slit (Blue) was observed by CGS4 of UKIRT in 2001, 2004. *(Lee et al. 2005)*

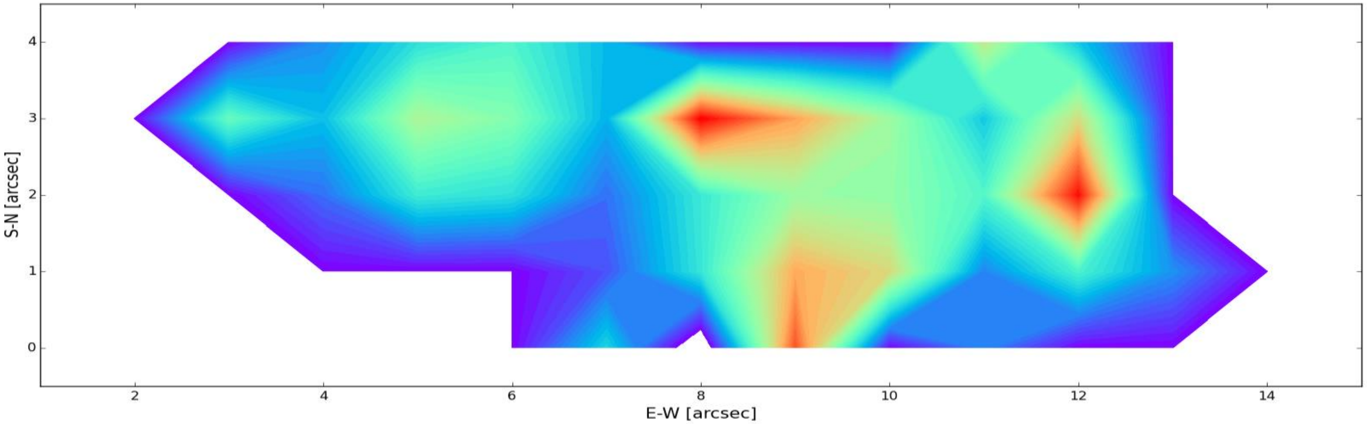
The region around the core of Hubble V is a dense PDR and suggest that there is no significant shock activity.
The moderate 2–1 S(1)/1–0 S(1) ratios (0.2–0.6) *(Lee et al. 2005)*

Analysis

- **Brγ**: H^+, Hydrogen recombination line.
- **H_2 observation**: The fundamental and most abundant molecule, tracing interaction between the star and the cloud – shocked region or PDR by Line ratio.

Line Intensity & Ratio of H_2 excitation 2-1 S(1) / 1-0 S(1)	
Thermal by shocks	Non-thermal by FUV
C-shocks : ~ 0.2 J-shocks : < 0.5 Slow J-shocks (< 24 km/s) : < 0.3	PDR ($n_{H2} < 5 \times 10^4$ /cm^3) : ~ 0.6 dense PDR : < 0.6

Line Ratios of $H_2$2-1 S(1) / H_2 1-0 S(1)



Line Ratios from Contour Map of Integrated Intensity of $H_2$2-1 S(1) / H_2 1-0 S(1).

- We get to know from Line Ratio: H_2 line excitation mechanism is PDR.
- As Collisional de-excitation increases (2-1)/(1-0) ratio becomes small. Therefore we can appreciate that the ratio is small, the object is dense.

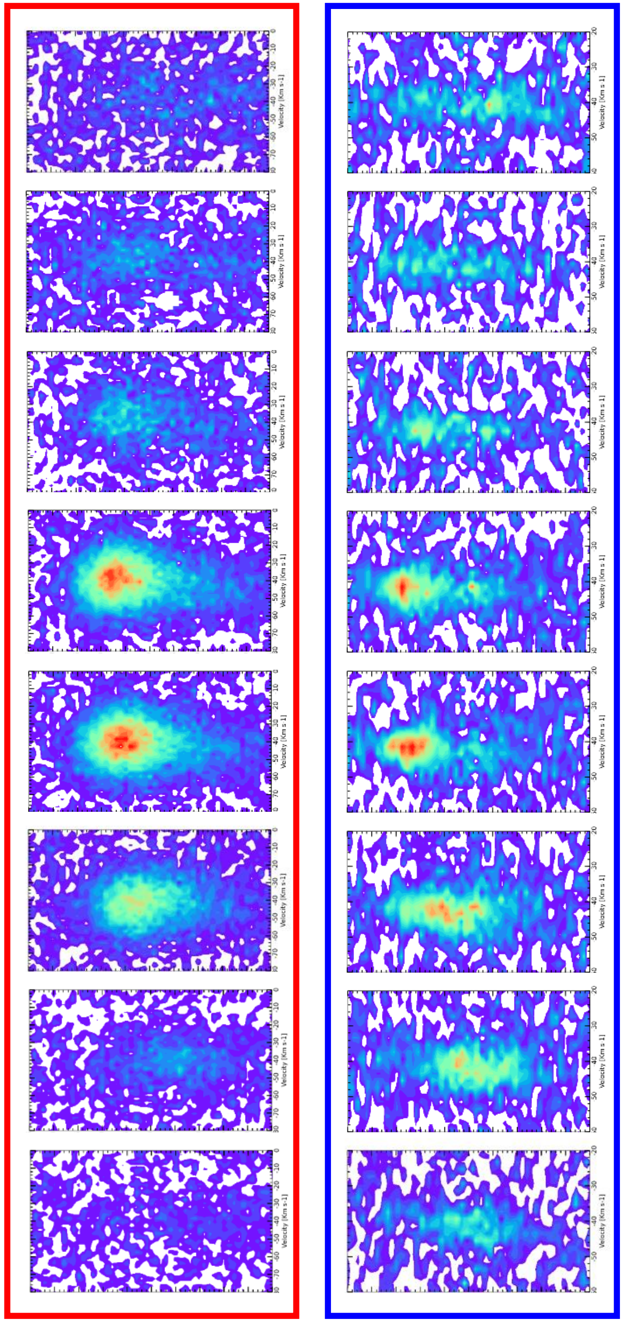
Position		$I_{1\text{-}0S(1)}$ [ADUs]	$I_{2\text{-}1S(1)}$ [ADUs]	$I_{2\text{-}1S(1)}/I_{1\text{-}0S(1)}$
P5	N 2”	107.6 (± 4.0)	39.5 (± 5.1)	0.367 (± 0.081)
P4	N 1”	97.8 (± 2.8)	32.7 (± 4.6)	0.334 (± 0.082)
P3	C	148.9 (± 2.9)	45.2 (± 3.6)	0.304 (± 0.045)
P2	S 1”	146.5 (± 4.9)	35.1 (± 4.2)	0.240 (± 0.060)
P1	S 2”	81.1 (± 4.6)	13.9 (± 3.5)	0.171 (± 0.106)

4. Result

PV Diagram

P8

P1

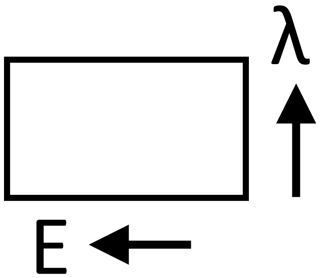


Brγ

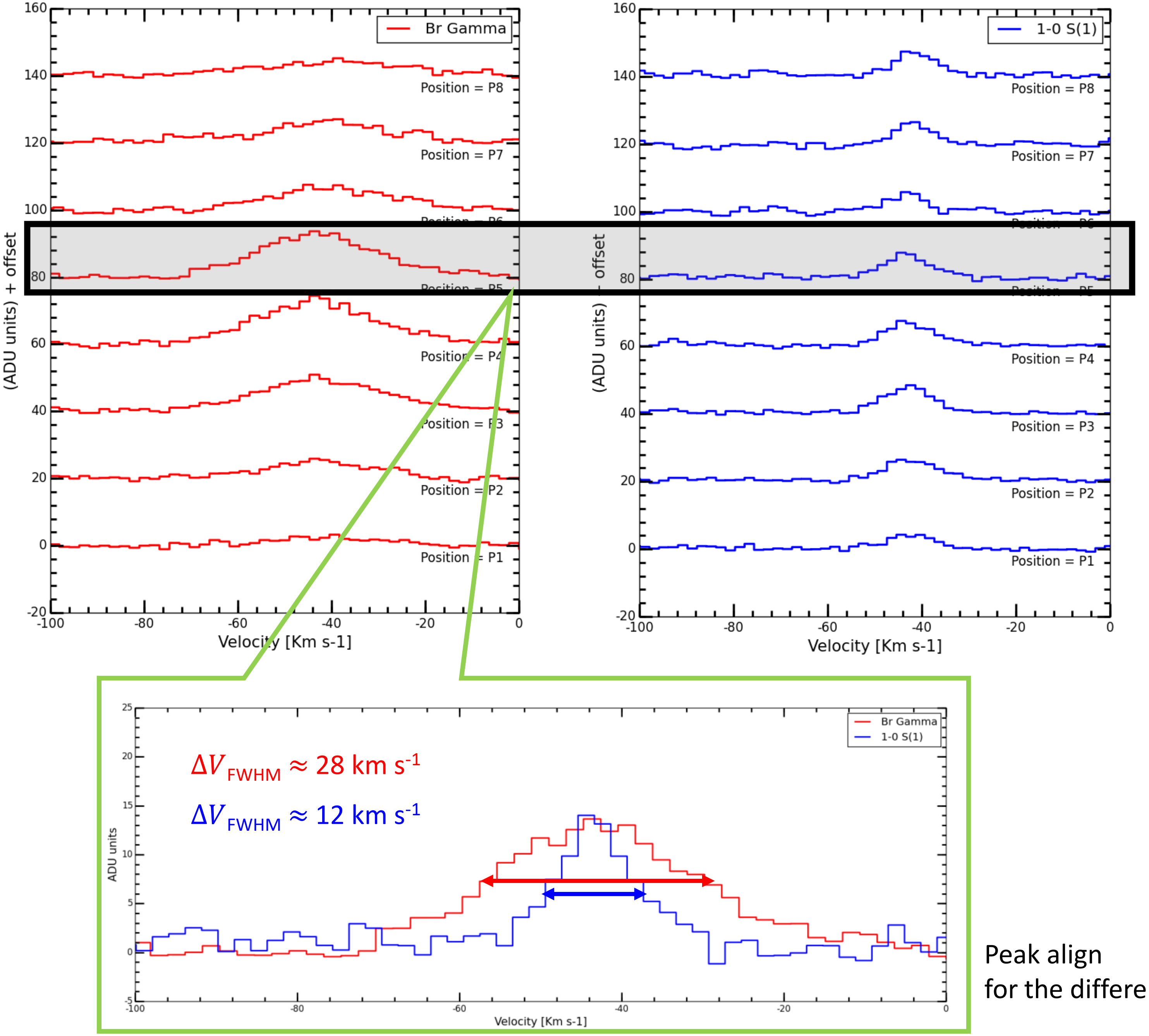
(- 80 < V_{LSR} < 0 km s^{-1})

H_2 1-0 S(1)

(- 60 < V_{LSR} < 20 km s^{-1})



RV Diagram



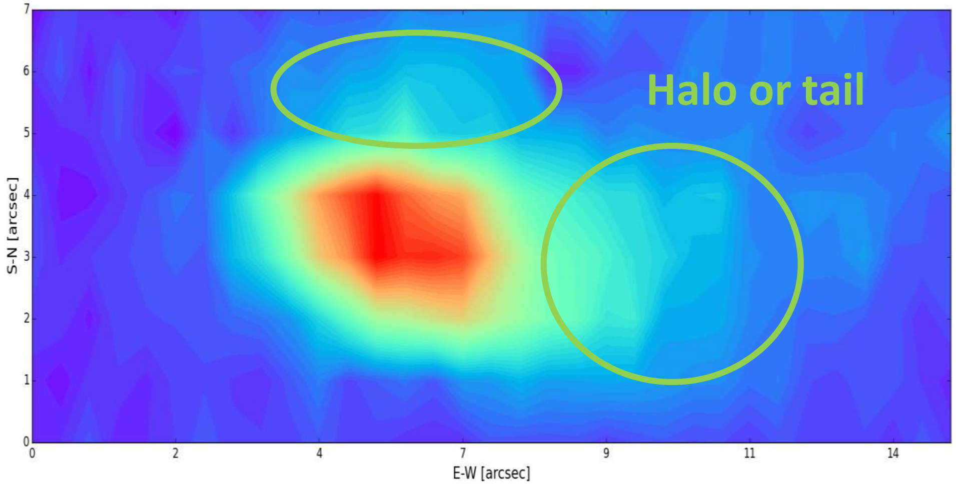
$\Delta V_{\mathrm{FWHM}} \approx 28\ \mathrm{km\ s^{-1}}$

$\Delta V_{\mathrm{FWHM}} \approx 12\ \mathrm{km\ s^{-1}}$

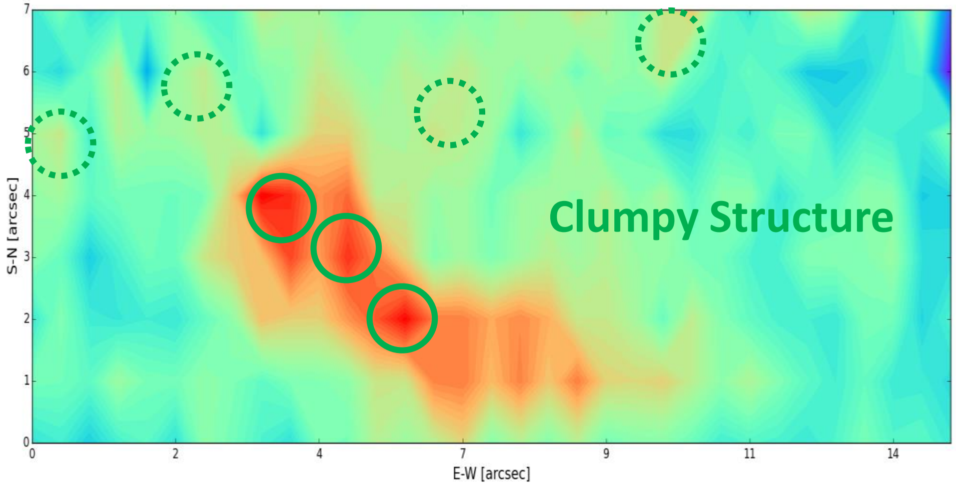
Peak align
for the different line width.

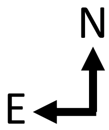
Color Map of Integrated Intensity

Brγ



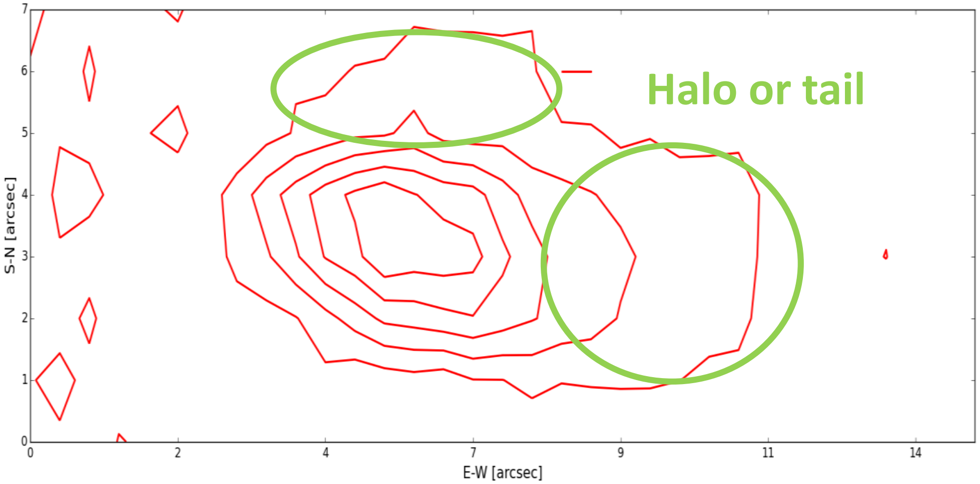
H_2 1-0 S(1)



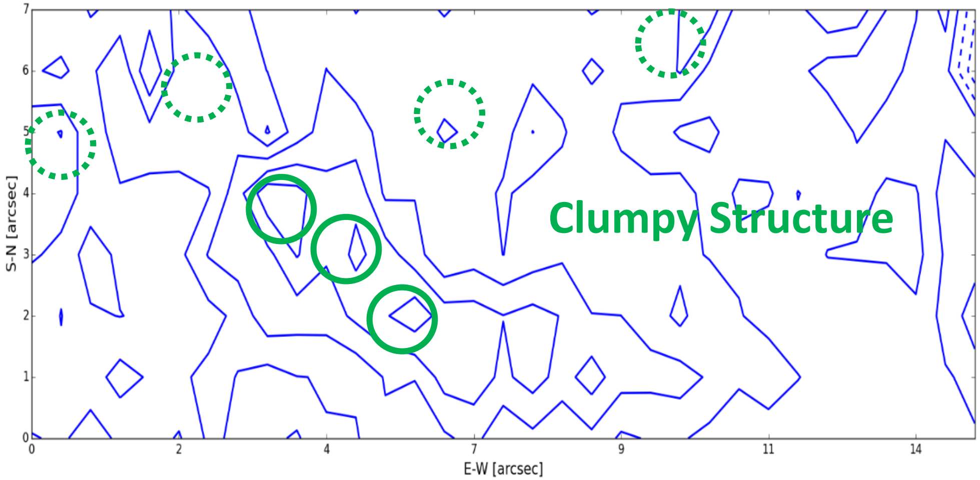


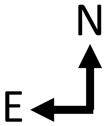
Contour Map of Integrated Intensity

Brγ

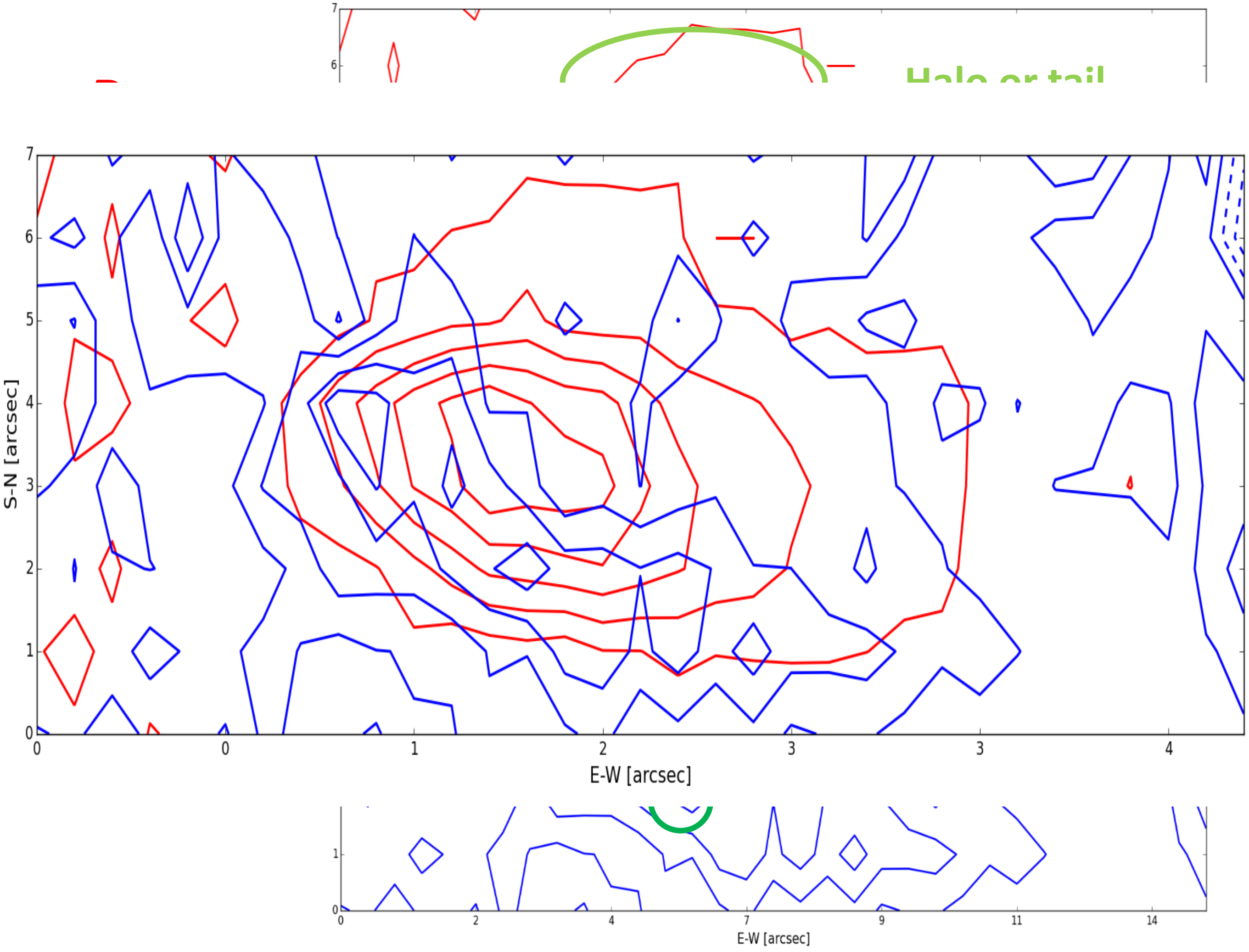


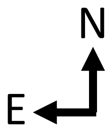
H_2 1-0 S(1)



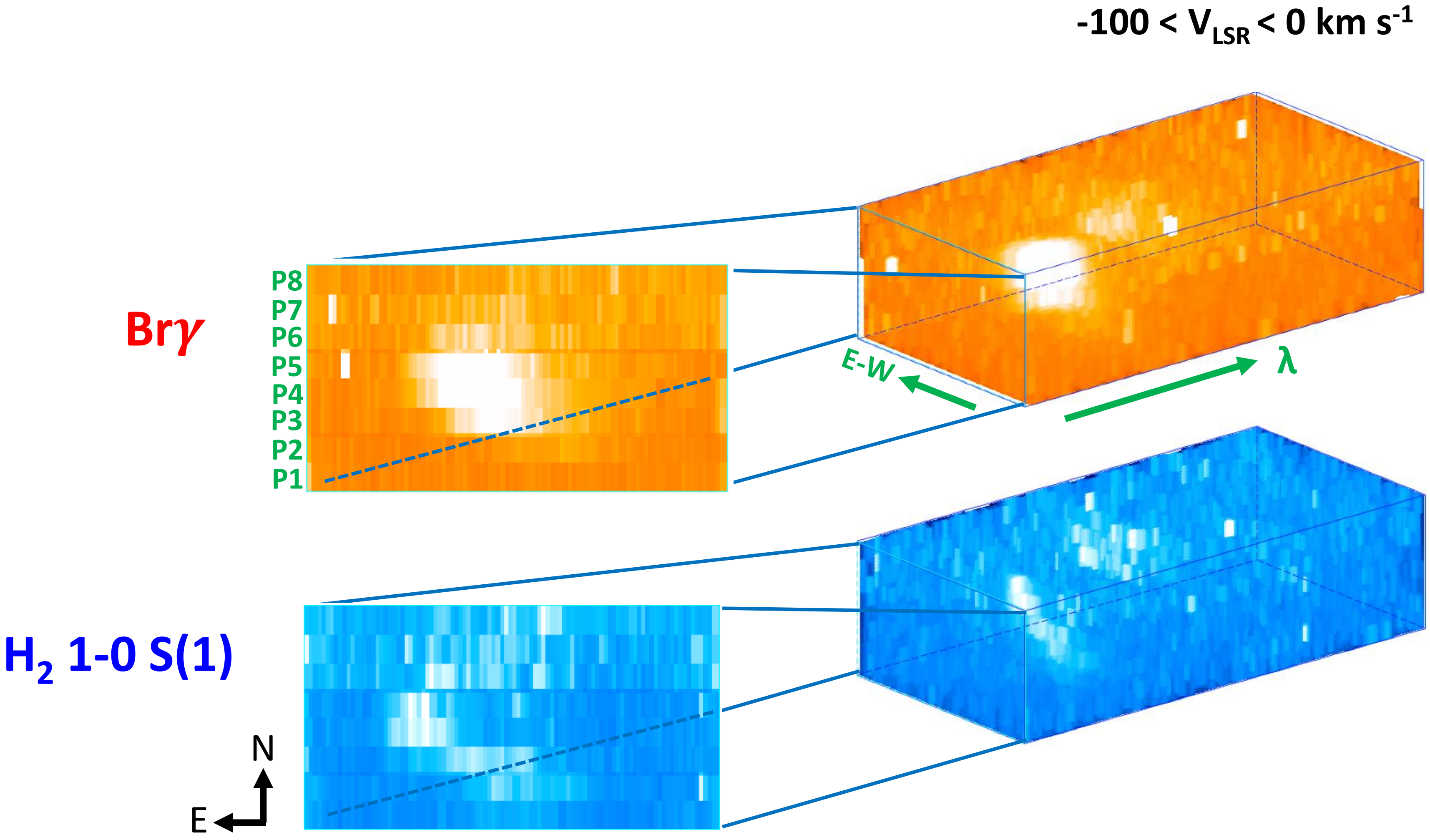


Contour Map of Integrated Intensity





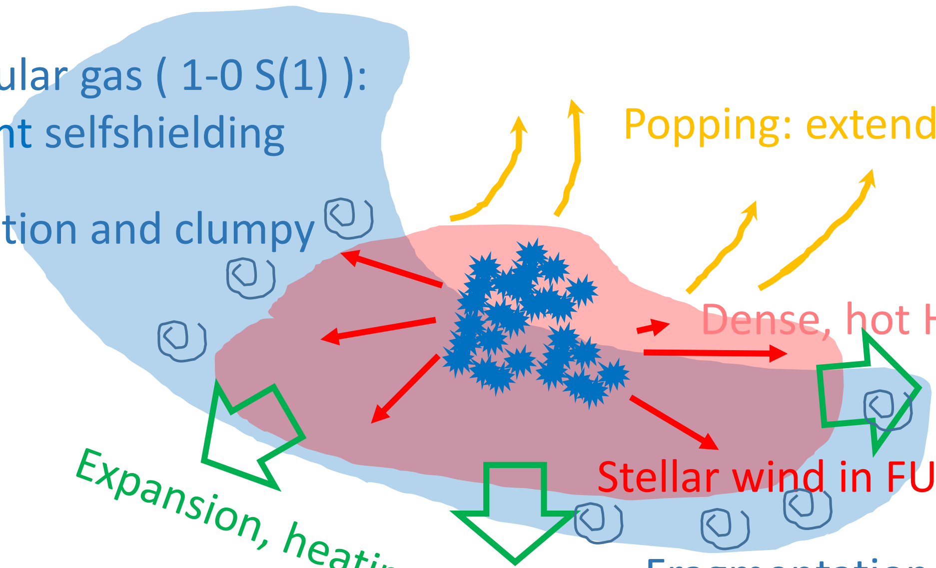
3D CubeData



5. Summary

NGC 6822 Hubble V has ‘Bubble’

✸ Embedded massive stars in OB associations and star-forming regions



H_2 molecular gas (1-0 S(1)): insufficient selfshielding

Popping: extending large and diffuse halo or tails

Fragmentation and clumpy

Dense, hot H I (Brγ) shell wall: strong velocity

Stellar wind in FUV, NUV of -41 km s^{-1}

Expansion, heating, ionization

Fragmentation and clumpy

NGC 6822 Hubble V has 'Bubble'

- We confirmed the structure suggested by Lee et al. (2005) through PV diagrams and the contours of integrated intensity, 3D cube of Br γ and H_2 1-0 S(1) from IGRINS observation. H_2 1-0 S(1) surrounds Br γ that extends towards the northwest.
- H_2 2-1 S(1) / H_2 1-0 S(1) line ratio increase from 0.17 to 0.37 (the south -> the north) & ~0.30 at the center region (UV excited ~0.6, and lower in denser PDR where collisions dominate). We need to analyze line ratio of molecular hydrogen in each positions.
- Instabilities in the dense swept-up circumstellar bubbles shells cause fragmentation and clumpy morphologies. We suggest that NGC 6822 Hubble V is a hot bubble with clumpy molecular structure.
- The feedback from massive stars is critical for the self-regulation of star formation, which can be quenched when the parental molecular cloud is disrupted, or even enhanced if the expanding gas destabilizes nearby molecular clouds, which collapse to produce new stars *(Gerola & Seiden 1978; McCray & Kafatos 1987; Palous, Tenorio-Tagle & Franco 1994).*