

The Molecular Baryon Cycle of M82

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Chisholm & Matsushita 2016, ApJ, 830, 72

Matsushita et al. 2005, ApJ, 618, 712

Matsushita et al. 2000, ApJL, 545, L107

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Background: NGC 7000 North America Nebula, by Dr. W.-H. Wang

Introduction

Baryon Cycle of Galaxies

er Galaxies lose gas by:

er Forming stars.

er High energy photons and cosmic rays from high-mass stars.

er Galactic outflows caused by supernovae.

er Galaxies gain gas by:

er Low velocity outflows recycle back.

er Accretion from circumgalactic medium.

er Major/minor mergers.

Introduction

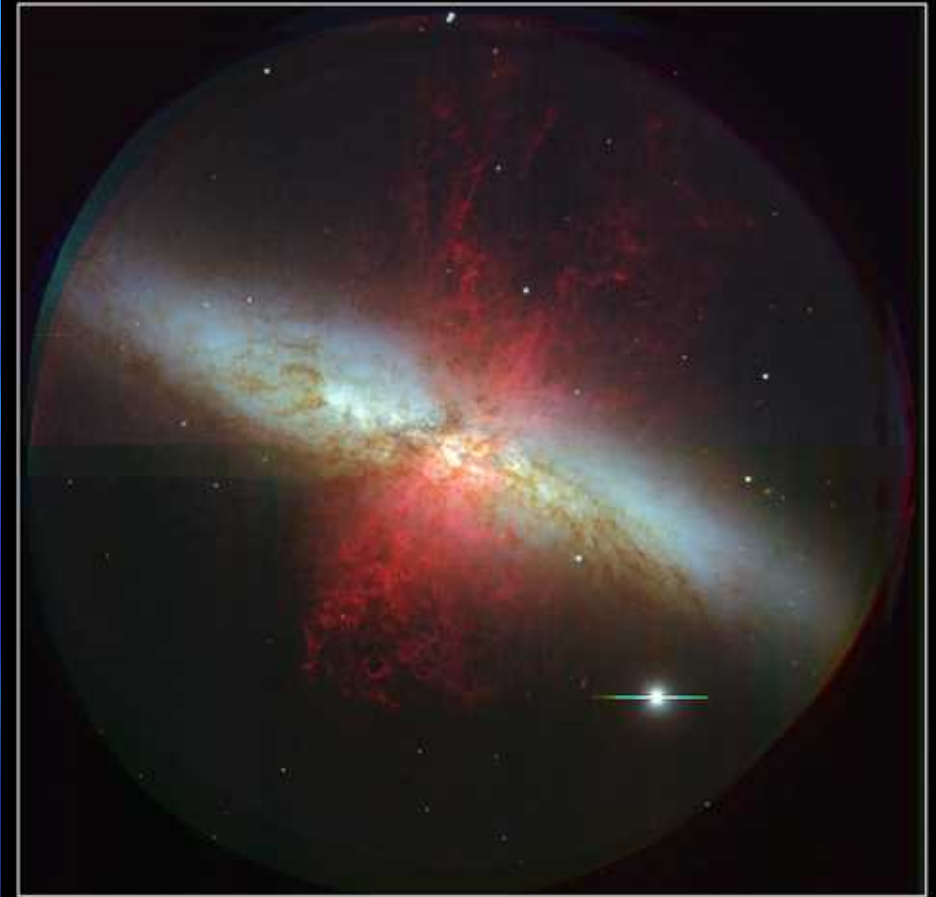
Molecular Gas

- er* Molecular gas makes stars.
 - er* Existence of (dense) molecular gas means the (future) location of star formation.
 - er* Molecular gas outflows take away the fuel for star formation.
 - er* Molecular gas inflows supply the fuel for star formation.
- er* Molecular gas observations will tell us the baryon cycle of galaxies.

Introduction

Prototypical Starburst M82

- er* One of the Nearest starburst galaxies (3.6 Mpc).
- er* H α , X-ray, Molecular Gas, & Dust Outflows.
- er* Many observations at various wavelengths in the past.



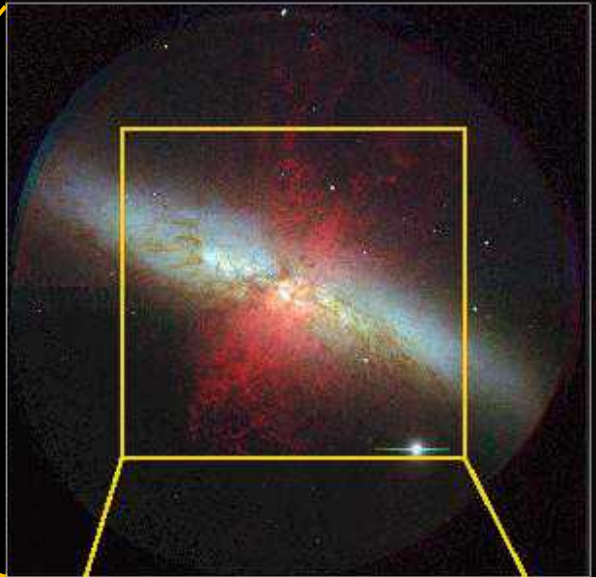
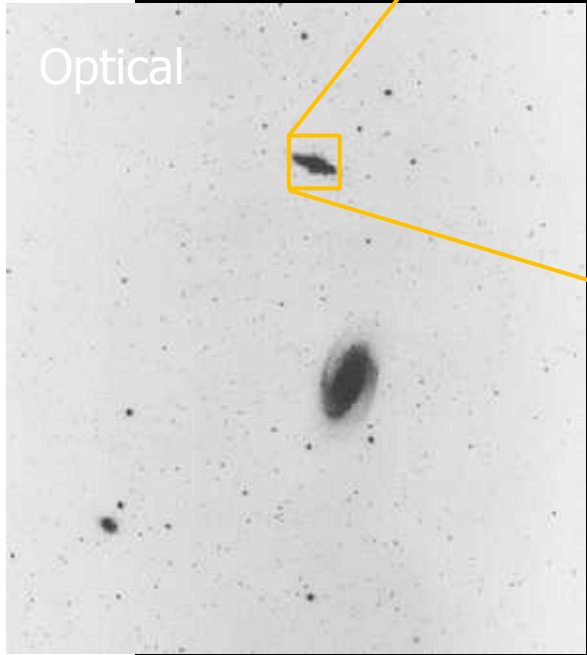
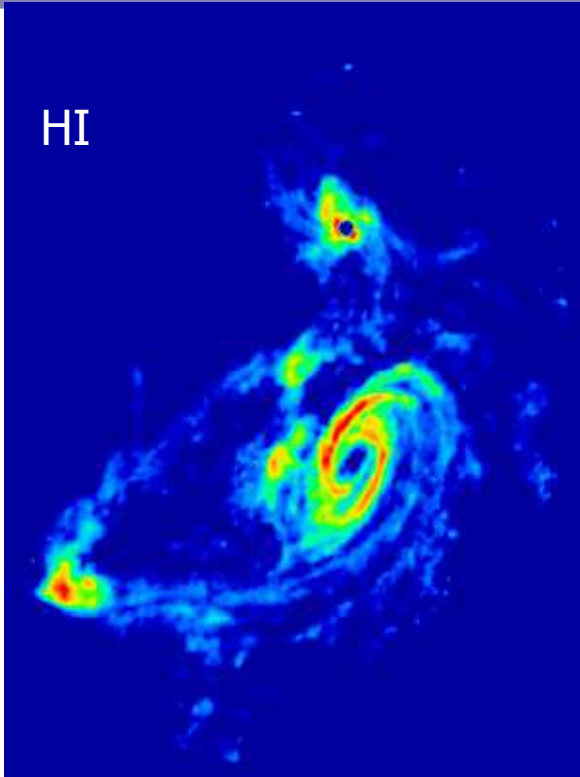
M 82 (NGC 3034)

Subaru Telescope, National Astronomical Observatory of Japan

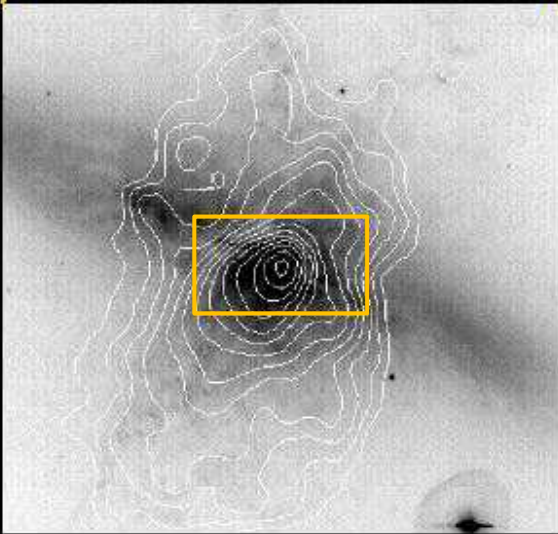
FOCAS (B, V, H α)

March 24, 2000

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M 82 (NGC 3034) FOCAS (B, V, H α)
Subaru Telescope, National Astronomical Observatory of Japan March 24, 2010
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372, 530

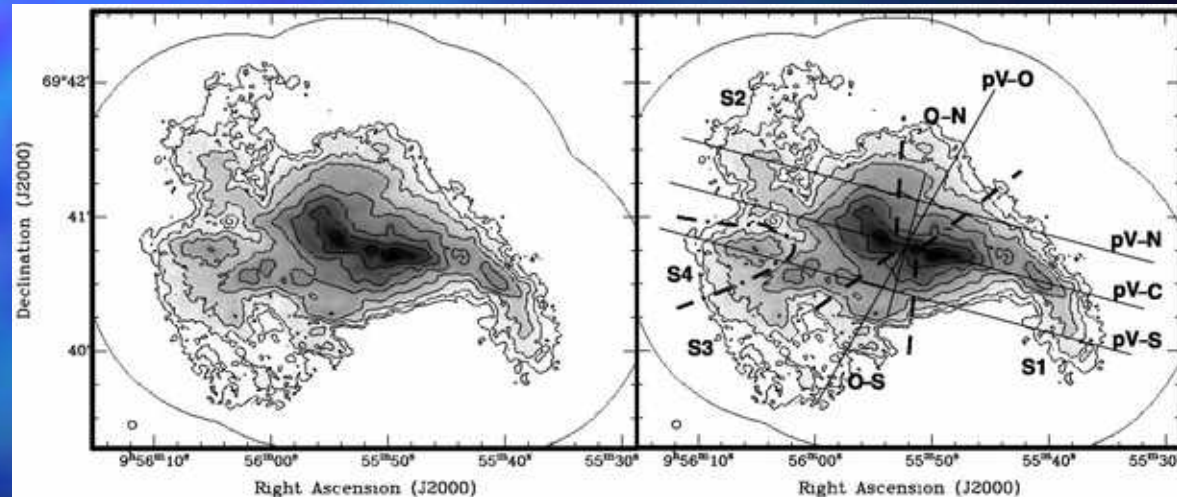
H α (Greyscale; Shopbell et al. 1998)
X-ray (Contours; Bregman et al. 1995)

Introduction


Molecular Gas Filaments

er Due to the tidal interaction and active star formation, many molecular filaments exist around M82.

Walter et al.
2002, ApJL, 580
L21



er We try to derive physical conditions and kinematics of the filaments.

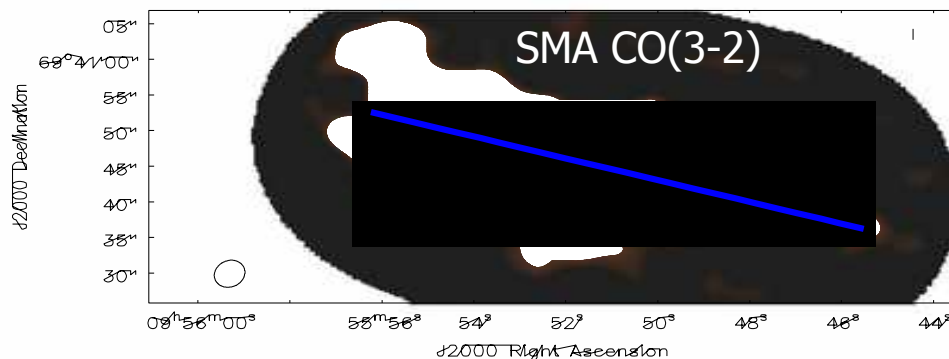
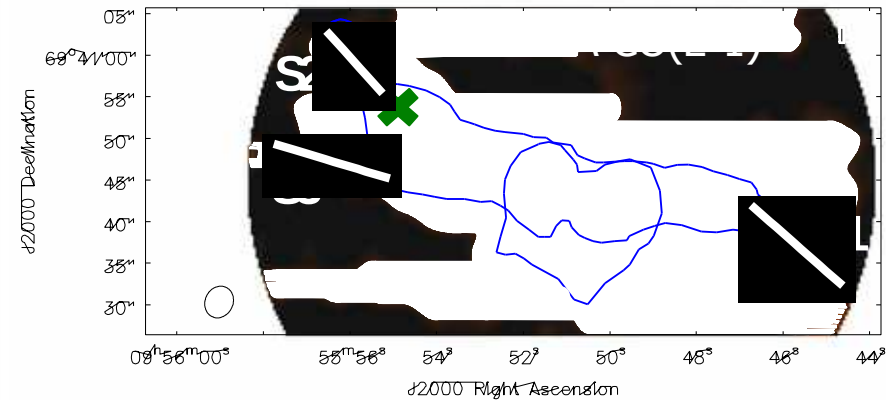
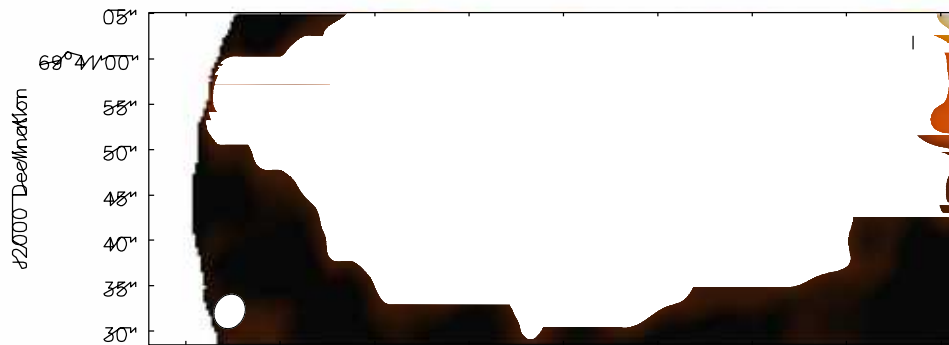


Results

Results

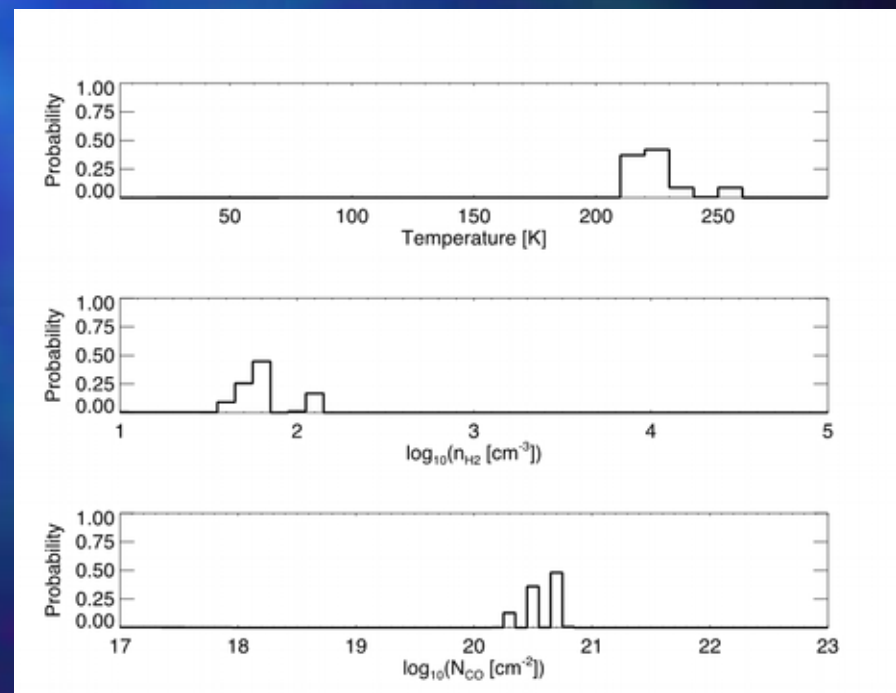
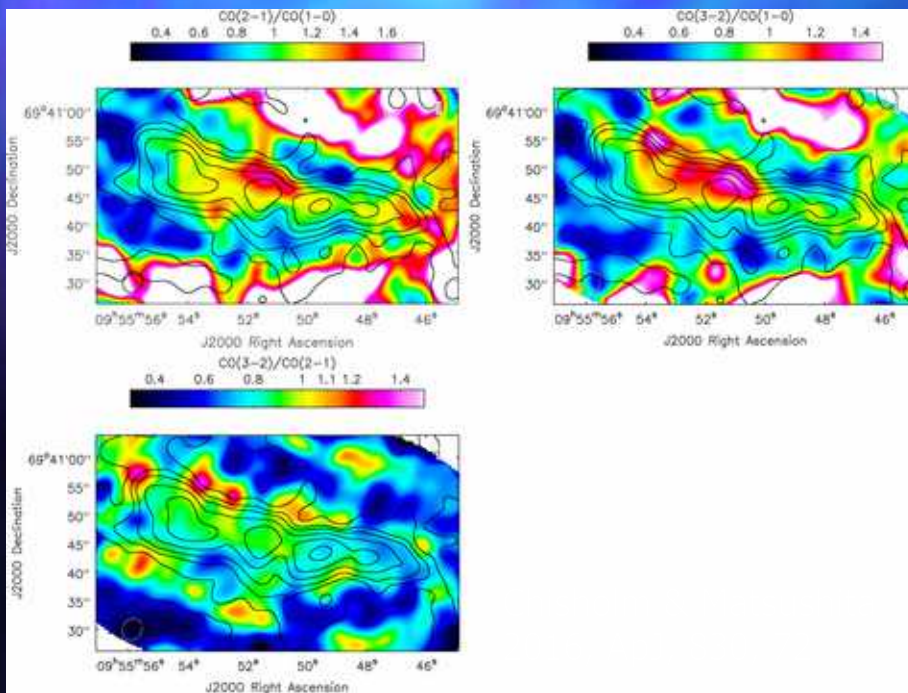
Multi-J CO Maps

Central region of M82 has been observed in CO J=1-0, 2-1, & 3-2.



RADEX + Bayesian Analysis

er To derive the physical conditions (density, temperature, and column density) of molecular gas, we used RADEX + Bayesian Analysis.



Overall Density & Temperature

er Density: $101.8 - 3.1 \text{ cm}^{-3}$

er Temperature: $61-175 \text{ K}$

er Each Component

er Disk

er Density: $102.6 \pm 0.5 \text{ cm}^{-3}$

er Temperature: $104 \pm 36 \text{ K}$

er Superbubble

er Inside Disk

- Density: $102.64 \pm 0.18 \text{ cm}^{-3}$

- Temperature: $82 \pm 17 \text{ K}$

er Outside Disk

- Density: $101.93 \pm 0.15 \text{ cm}^{-3}$

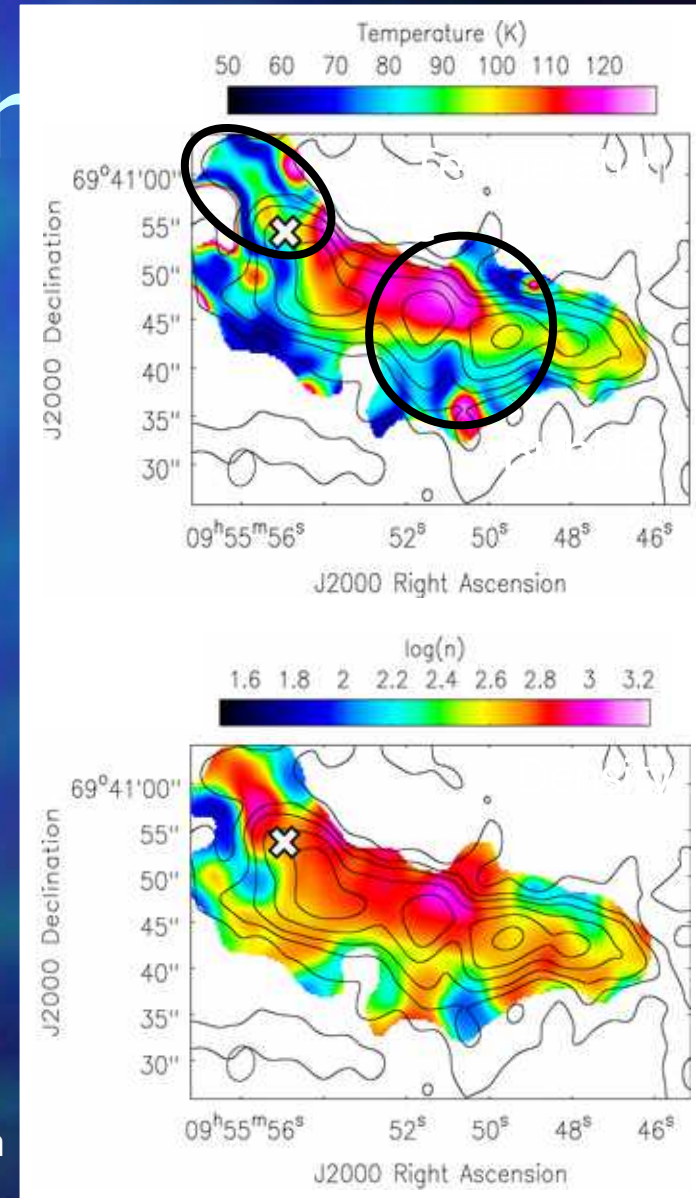
- Temperature: $159 \pm 30 \text{ K}$

er Filament S2

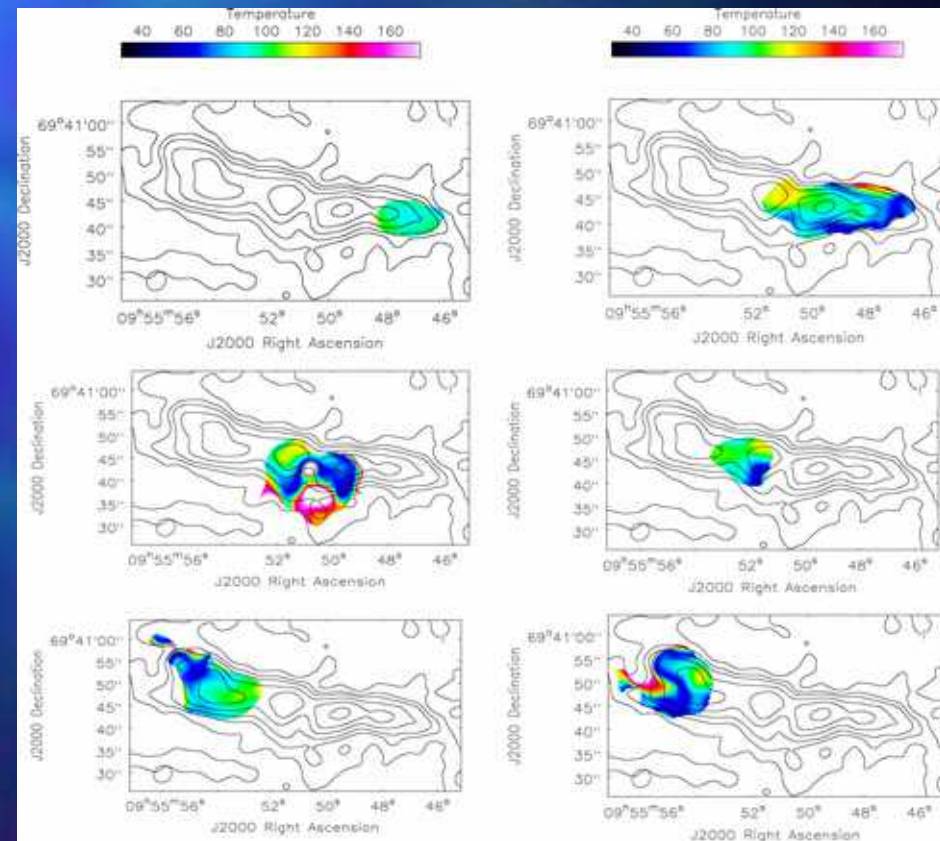
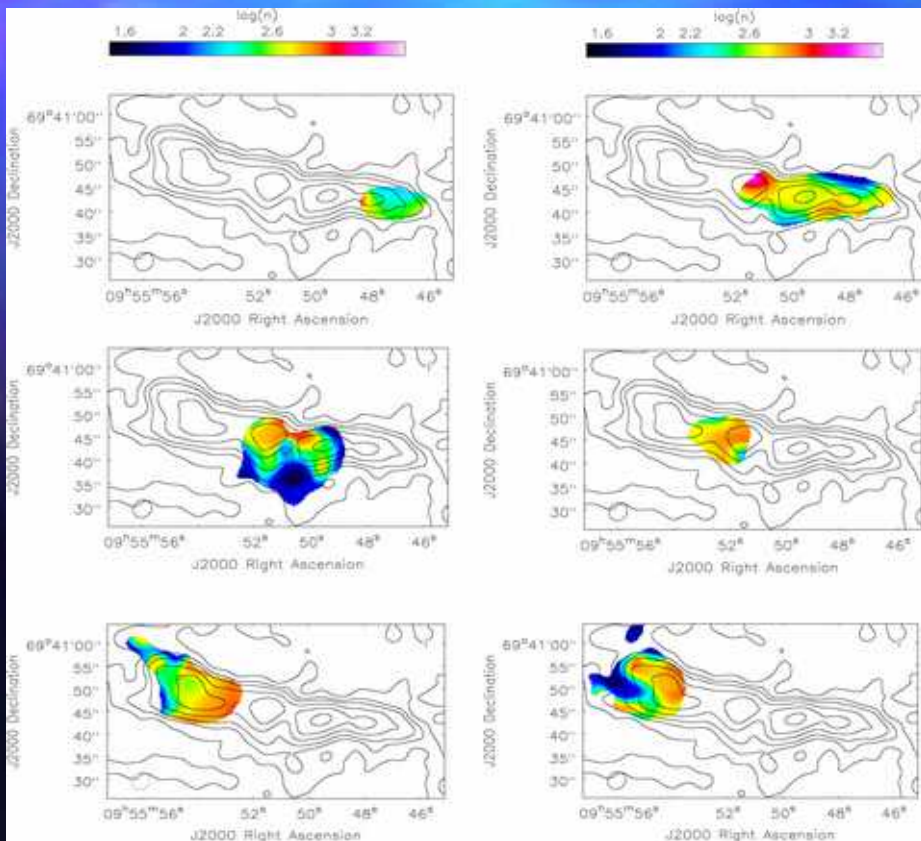
er Density: 102.3 cm^{-3}

er Temperature: 128 K

Chisholm & Matsushita
2016, ApJ, 830, 72

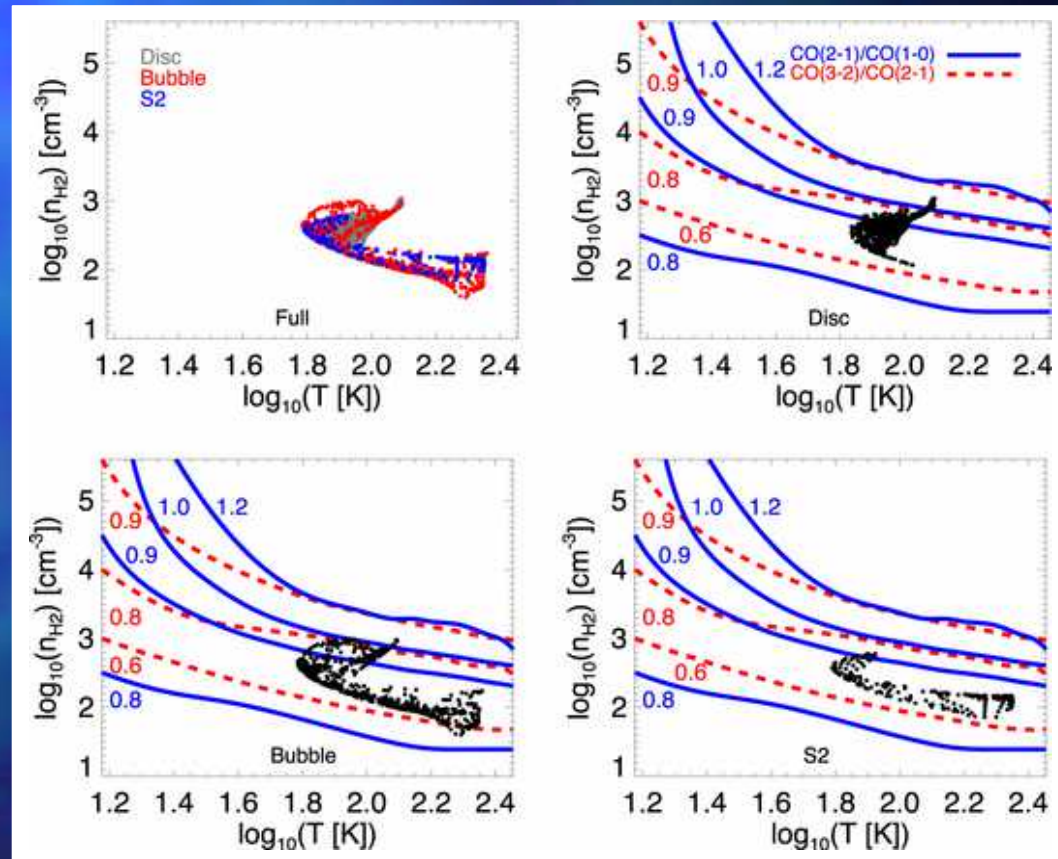


Density & Temperature Channel Map



Density vs Temperature

er Superbubble and the streamer S2 have diffuse and high temperature components.



CO-to-H₂ Conversion Factor X_{CO}

0

er $N_{H_2} = X_{CO} \times (I_{CO} \times dv)$

$\Rightarrow X_{CO} = (N_{CO} / dv) / \{Z(CO) \times I_{CO}\}$

$n(H_2) \times \{Z(CO)/(dv/dr)\} / \{Z(CO) \times I_{CO}\}$

(Sakamoto et al. 1999)

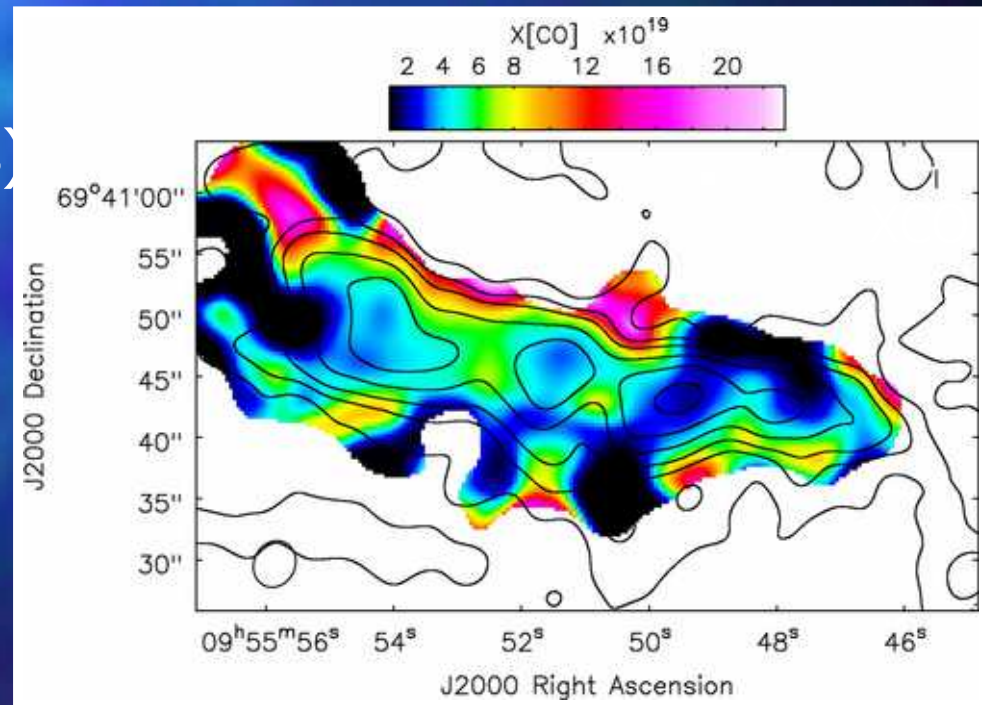
er Median X_{CO}

$\sim 4 \times 10^{19} \text{ cm}^{-2} / (\text{K km/s})$

er An order of magnitude smaller than that in our Galaxy.

er Total Molecular Gas Mass

$\sim 2 \times 10^8 \text{ Msolar}$

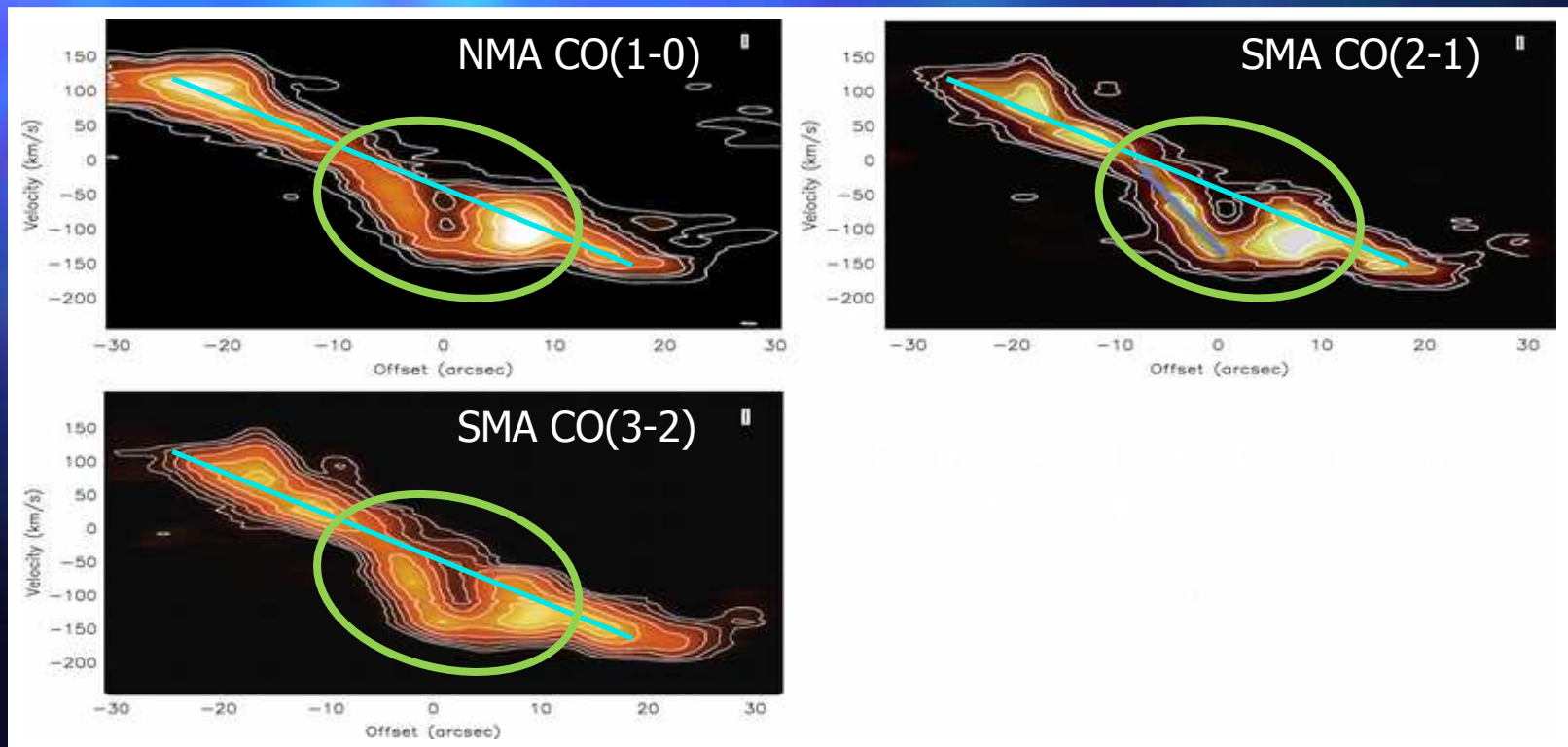




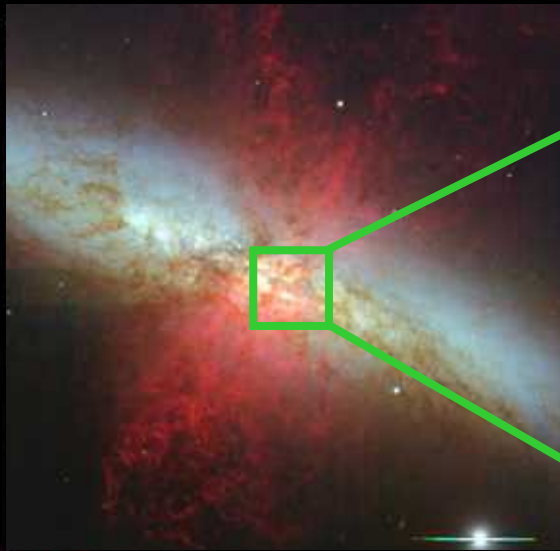
Self-Induced Starburst inside the Molecular Superbubble

Molecular Gas Kinematics

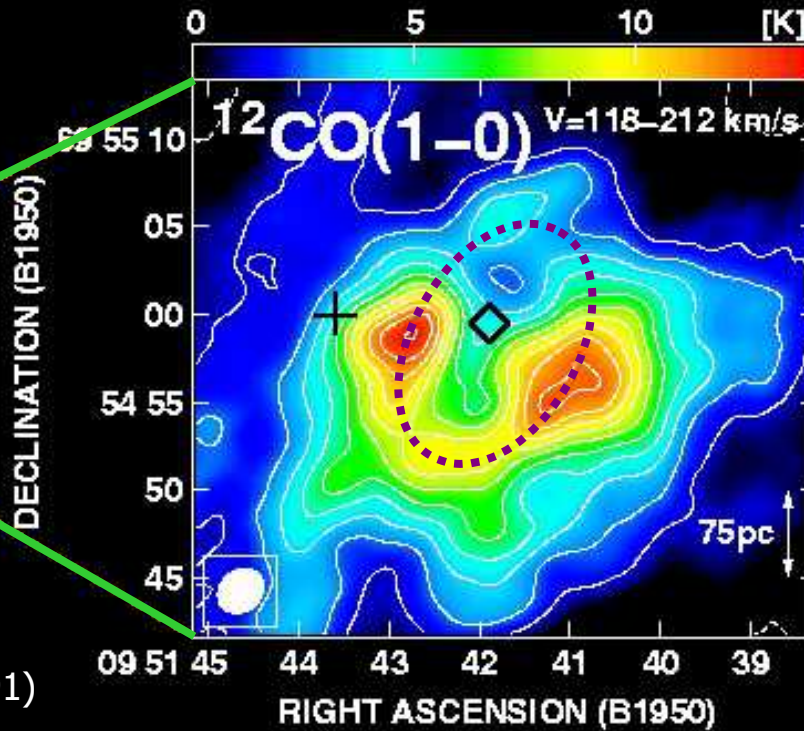
er There is a significant offset from the rigid rotation near the galactic center.



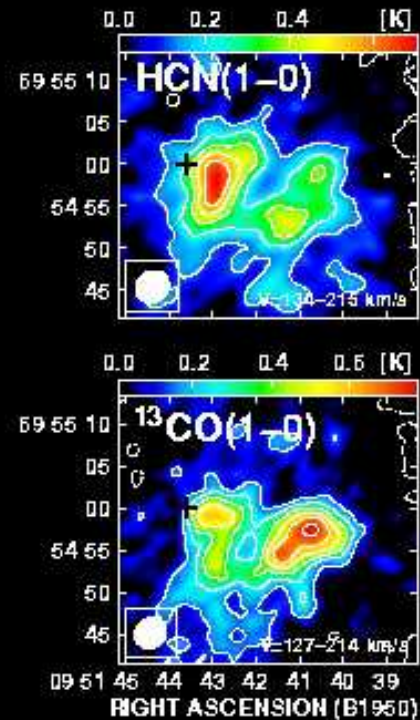
Molecular Superbubble in M82



Subaru H α + B, V-band
(Ohyama et al. 2002, PASJ, 54, 891)



+ 2.2 μ m Peak (Nucleus)
◇ 2.2 μ m Secondary Peak



*Nobeyama Millimeter Array
Matsushita et al. (2000)*

er 140 pc offset from the galactic center.

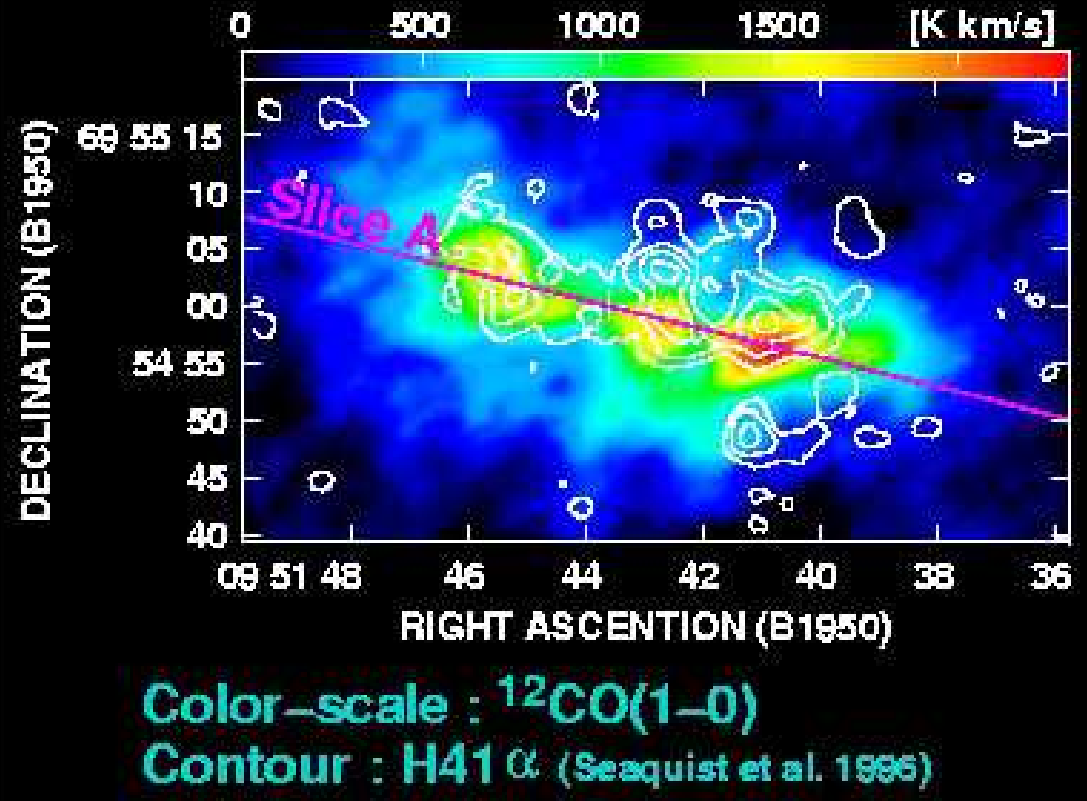
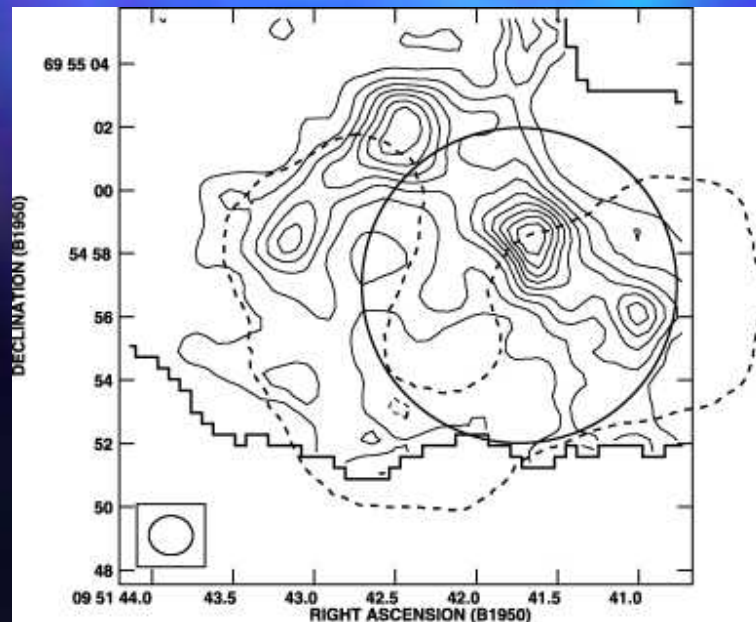
➤ Localized.

er Visible in both diffuse and dense molecular gas

➤ Most of the molecular gas is associated with the bubble.

Atomic and Ionized Gas at the Superbubble

- er Different distribution
- er South part : Mainly molecular gas
- er North part : Mainly atomic/ionized gas



- er Contour : HI Absorption
(Wills et al. 2002, MNRAS, 331, 313)
- er Dashed Line : CO Superbubble

Molecular Superbubble in M82

Properties

Size $\sim 210 \times 140$ pc

Elongated perpendicular to the galactic disk.

Expansion Velocity $\sim 50 - 100$ km/s

Age $\sim (1-2) \times 10^6$ yr

Mass $\sim (1-3) \times 10^8$ Msolar

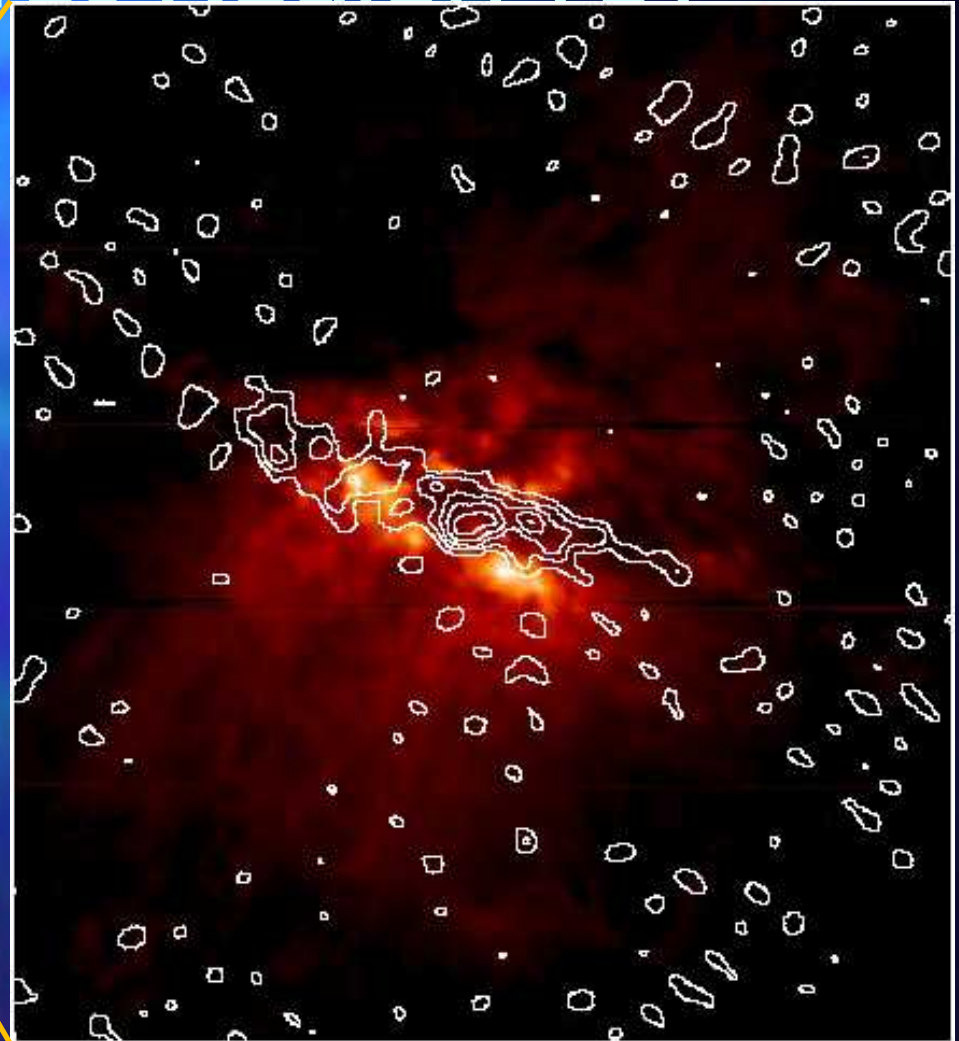
Energy $\sim (0.5-2) \times 10^{55}$ erg

Equivalent to 10^3-10^4 supernovae energy.

Mass Outflow Rate ~ 17 Msolar/yr

Starbursts inside the Superbubble Present Starburst Region (1)

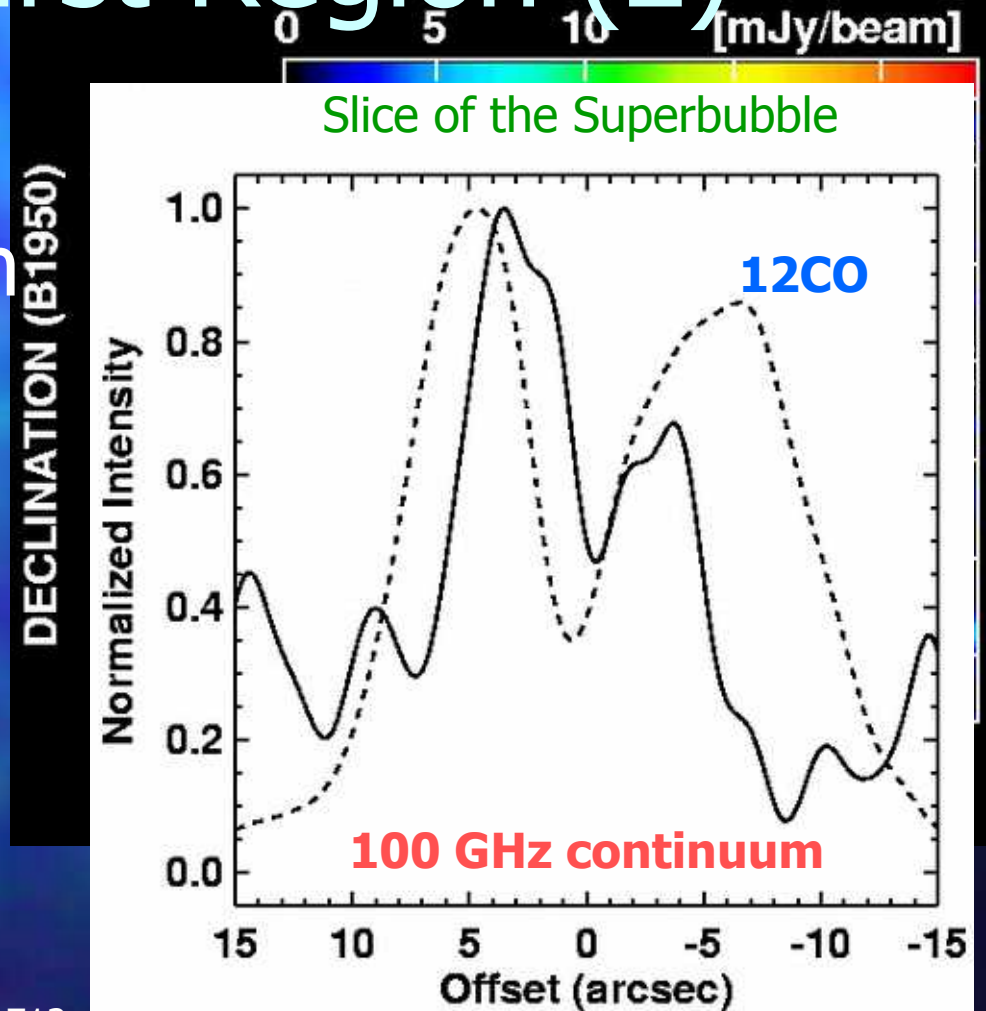
et Most of the starburst regions are obscured by dust.



- * Color : H ϵ emission
(Ohyama et al. 2002, PASJ, 54, 891)
- * Contour : 100 GHz continuum
(Matsushita et al. 2005, ApJ, 618, 712)

Starbursts inside the Superbubble Present Starburst Region (2)

- Peak positions of 100 GHz continuum are offset from the nucleus.
- Starburst regions are inside edge of the superbubble.
- Starburst is weak at the bubble center.



Self-Induced Starburst in M82

Termination of Starburst

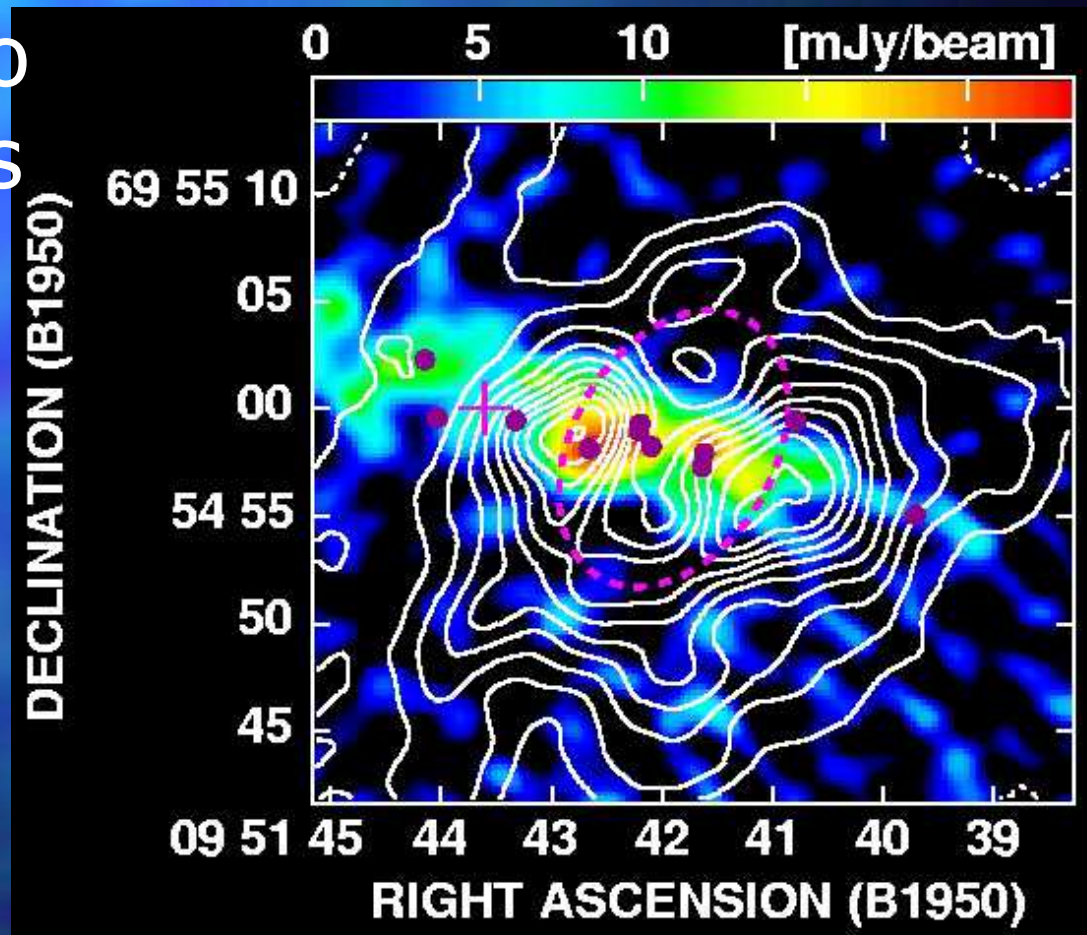
- er* Stars are made from (dense) molecular gas.
- er* Small amount of molecular gas at the center of the superbubble.
- er* Free-free emission is also weak.
- er* Red supergiant dominated star cluster locates at the center of the superbubble.



- er* Starburst at the center of the superbubble begins to cease.
- er* Number of massive stars is decreasing by supernova explosions.

Starbursts inside the Superbubble Atomic, Ionized Gas, & Masers (1)

er Masers are well correlated with the starburst regions.



- * Color : 100 GHz continuum
(Matsushita et al. 2005, ApJ, 618, 712)
- * Contour : 12CO Superbubble
(Matsushita et al. 2000, ApJL, 545, L107)
- * Dots : OH & H₂O Masers
(Wellachew et al. 1984; Seaquist et al. 1997;
Baudry & Boulliet 1996)

Starbursts inside the Superbubble Atomic, Ionized Gas, & Masers (2)

et Ionized gas expands faster.

et Many masers at the superbubble.

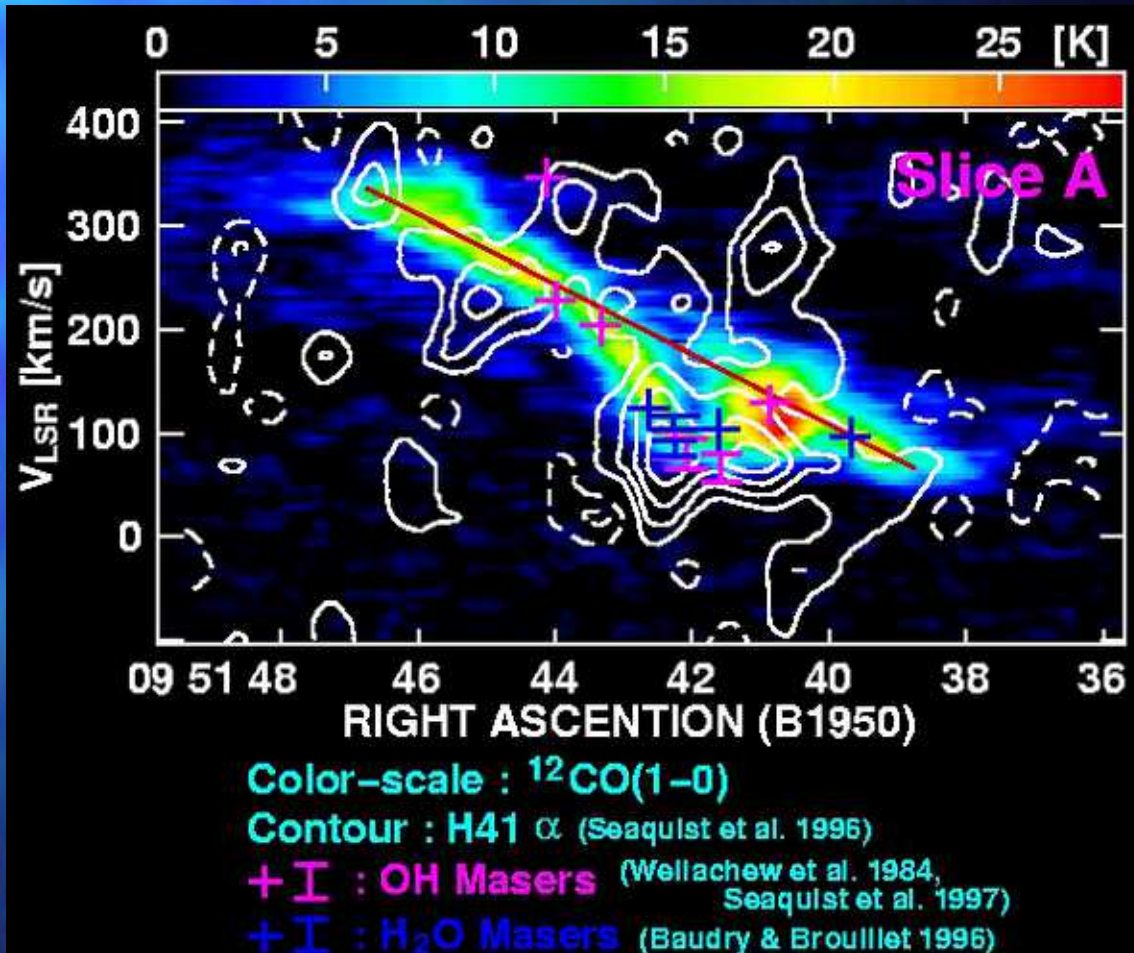


et Ionized gas is

et in the bubble.

et expanding toward outside.

et interacting with molecular gas.



Starbursts inside the Superbubble

Atomic, Ionized Gas, & Masers (3)

er Diffuse hard X-ray (2-8 keV; Griffiths et al. 2000, Science, 290, 1325) emits from inside the superbubble

er Size = $7.2'' \times 5.4''$
= 3.25 Mpc

er LX (2-10 keV) = 2.2×10^{39} erg/s

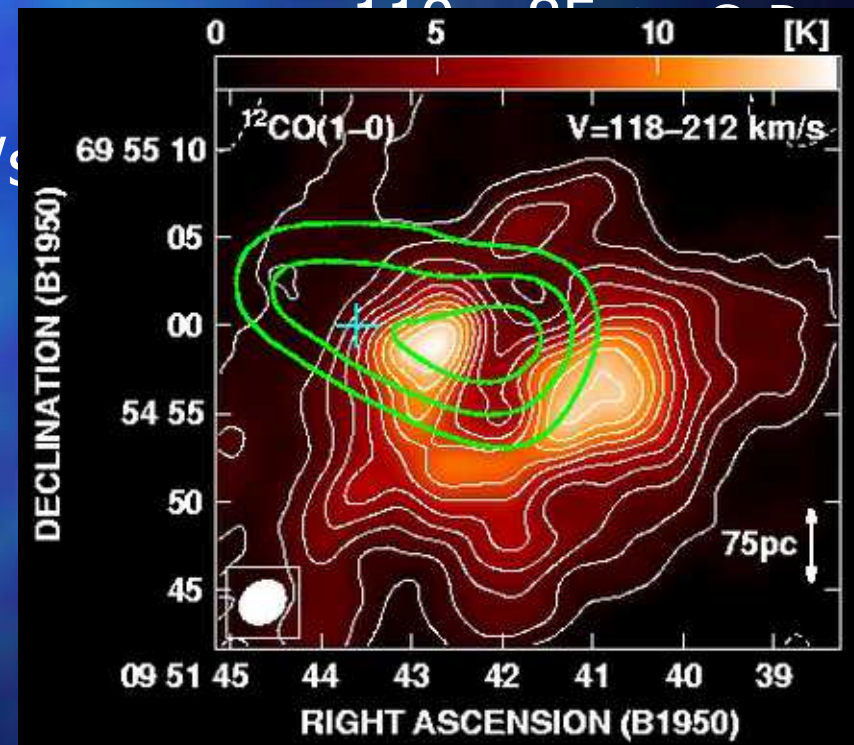
er $kT \sim 2.4 - 4.1$ keV

er Overpressurized
($n \sim 10^3 \text{ cm}^{-3}$).



er Bounded in the bubble.

er Consistent with the results
of masers.



er Green Contour: Diffuse Hard X-ray

Starbursts inside the Superbubble

Diffuse Hard X-ray (2)

er Sound Speed of Plasma Proton $c_{pp} \sim \sqrt{(kT/m_p)} \sim (5-6) \times 10^2 \text{ km/s}$

er Expansion Timescale $t_{ex} \sim r/c_{pp} \sim (1-2) \times 10^5 \text{ yr}$



er Faster expanding velocity & short expansion timescale than the molecular superbubble



er Consistent with the results of ionized gas and masers.

Self-Induced Starburst in M82

Self-Induced Starburst

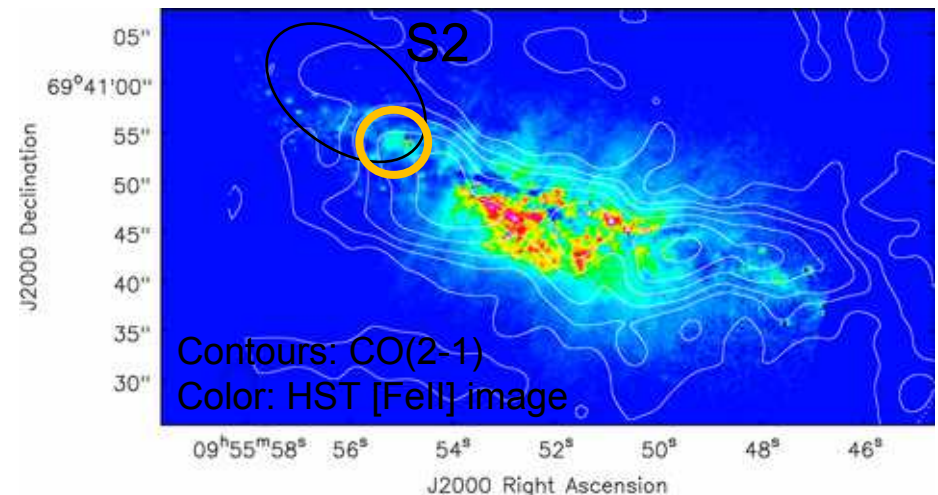
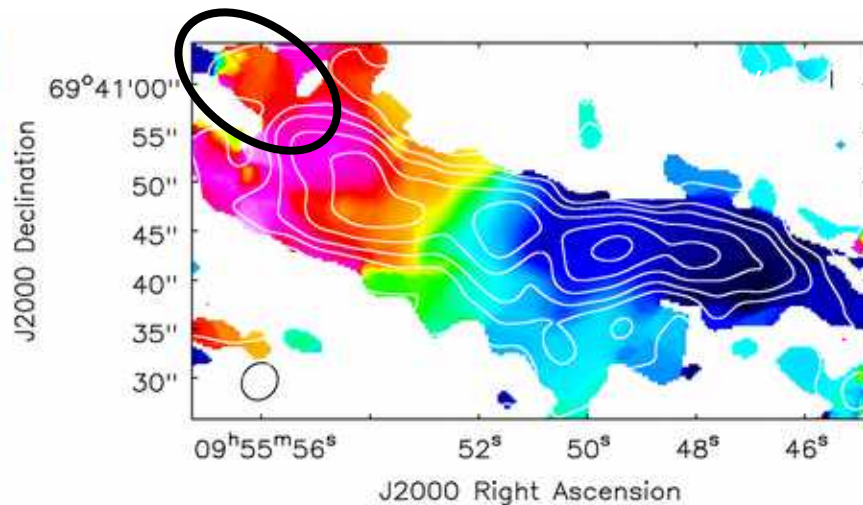
- er* Existence of the expanding molecular superbubble.
 - er* Bright supergiants (late OB stars) are at the center.
 - er* Overpressurized hot gas & high-velocity ionized gas.
 - er* Masers are concentrated.
 - er* Free-free emission is strong (= many massive stars exist) at the edge of the superbubble.
-
- er* Past starburst produced the high-velocity gas, swept surrounding gas, and produced the superbubble.
 - er* The compression of surrounding gas induced new starburst regions (Self-Induced Starburst).



Inflowing Filament S2

Inflowing Filament S2

- er Filament S2 is blueshifted (-37 km/s) from the galactic rotation.
- er If far-side, it is coming toward us, so "inflow".
- er If near-side, it is moving away from us, so "outflow".
- er S2 has $AV \sim 28$ mag, but no absorption feature in optical image.



Inflowing Filament S2

Properties

er Mass $\sim 1.5 \times 10^6$ Msolar

er Velocity Gradient $\sim 9 \times 10^{-7}$ yr⁻¹

er Mass Inflow Rate ~ 1.4 Msolar/yr

Molecular Baryonic Cycle of M82

er Total Molecular Gas Mass $\sim 2 \times 10^8$ Msolar

er Inflow Rate

er Filament S2

er H₂ + HI Gas Mass Inflow Rate ~ 3.5 Msolar/yr

er Consumption/Outflow Rate

er Star Formation Rate ~ 13 Msolar/yr (Förster Schreiber et al. 2003)

er Superbubble Outflow Rate ~ 17 Msolar/yr

er M82 will consume or expel all of the observed molecular gas in 7.8 Myr.

Molecular Baryonic Cycle of M82

Summary

- e*r We observed the starburst region of M82 in CO J=1-0, 2-1, & 3-2.
- e*r Density, temperature, XCO, and total molecular gas mass have been derived.
- e*r Self-induced starburst has been observed at the superbubble.
- e*r Observed gas inflow rate is much smaller than the consumption/outflowing rate, so that it will be consumed/expel in 7.8 Myr.