Evidence for dynamically important magnetic fields in massive star and cluster formation in RCW57A

Eswaraiah Chakali
Postdoc, Institute of Astronomy
NTHU, Taiwan

Shih-Ping Lai, Tao-Chung Ching, Jia-Wei Wang
(NTHU, Taiwan)
W. P. Chen (NCU, Taiwan), M. Tamura (NAOJ, Japan), Dan P. Clemens (BU, USA),
A. K. Pandey, G. Maheswar, S. Sharma
(ARIES, India)
A. M. Magalhaes (USP, Brazil), S. Nishiyama (MUE, Japan), J. Kwon (NAOJ, Japan)
Y. Nakajima (HU, Japan), C. R. Purcell (SifA, Australia)

SMA science in the next decade
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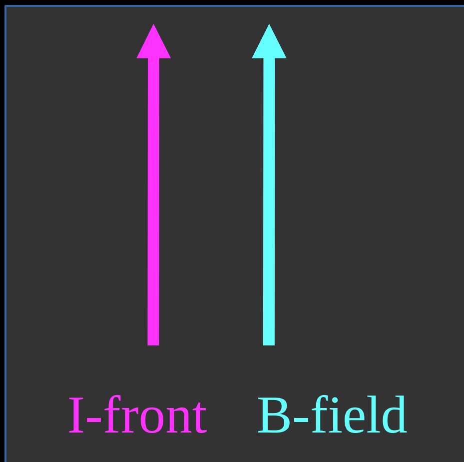
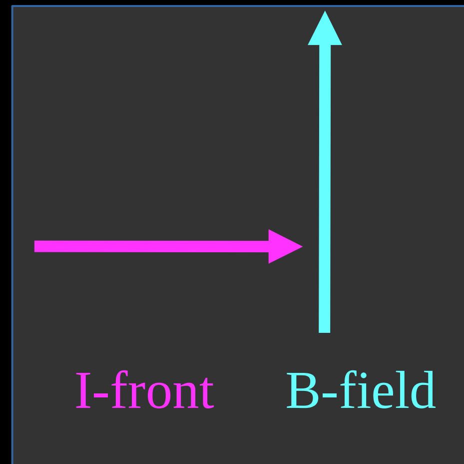
ASIAA

Influence of B-fields on expanding ionization fronts



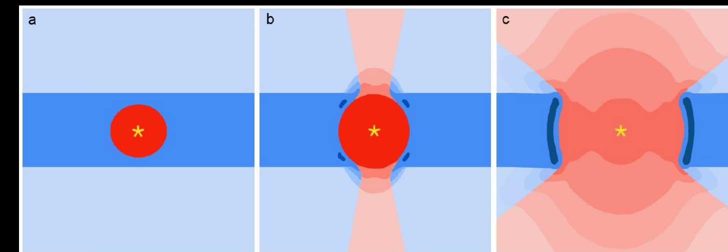


I-fronts ==> accelerated

==> hindered

B-fields provide anisotropic pressure

Filament => HII region => bipolar bubble
(2D HD simulations: Bodenheimer+ 1979; Deherveng+ 2015)

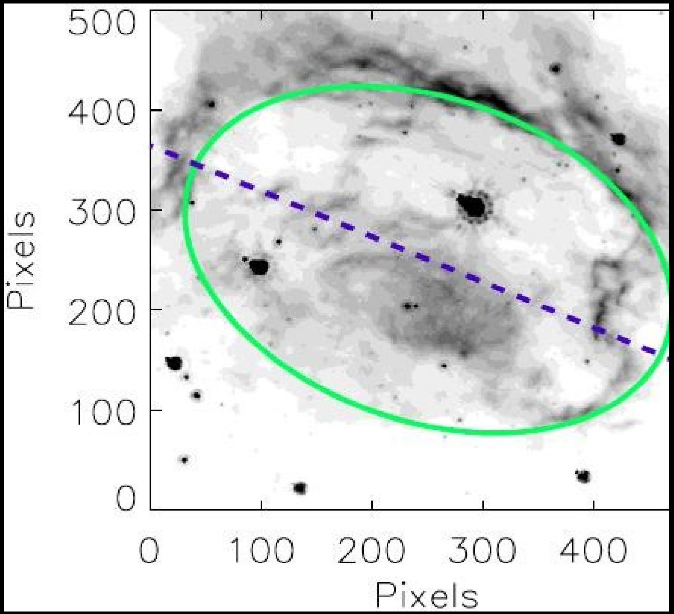


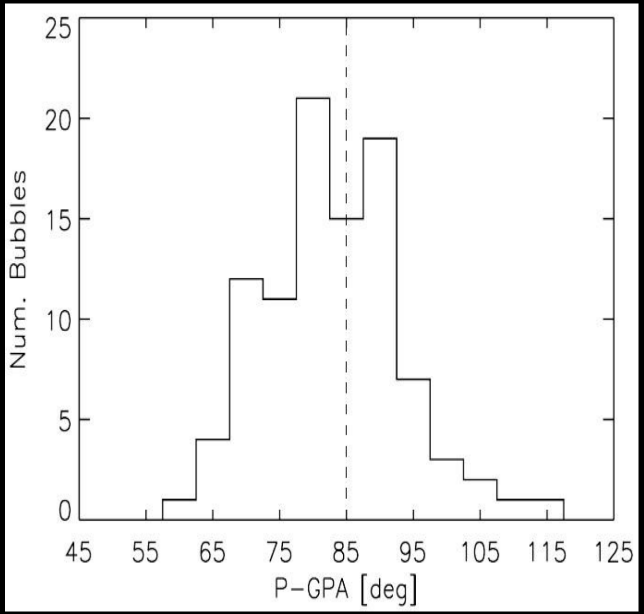
B-fields may affect: opening angle & the extent they expand

Eg., Galactic bubbles of young HII regions elongated along B-field in Galactic plane.

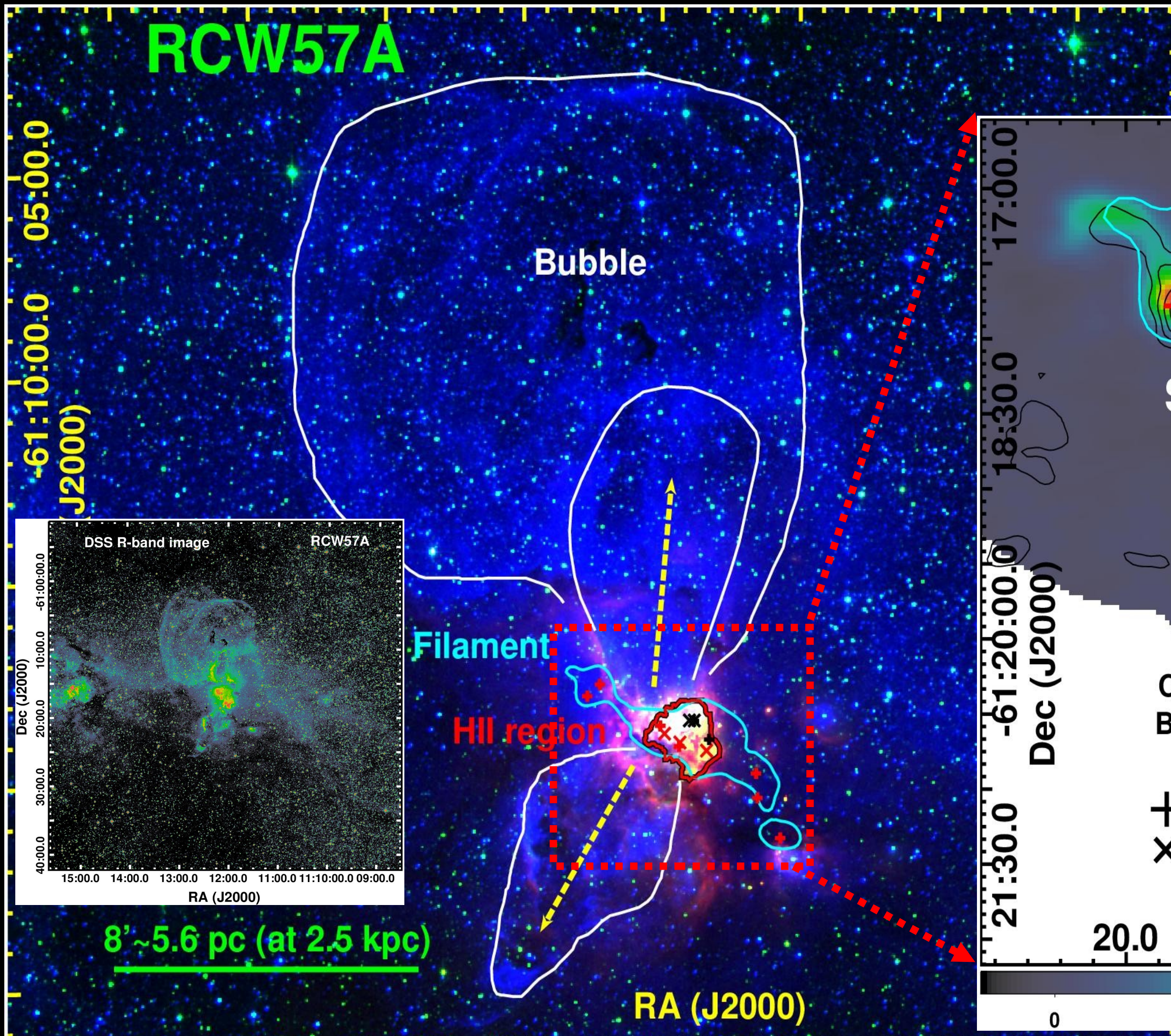
Easier for charged particles to follow B-fields than perpendicular to them

(Pavel & Clemens 2012)

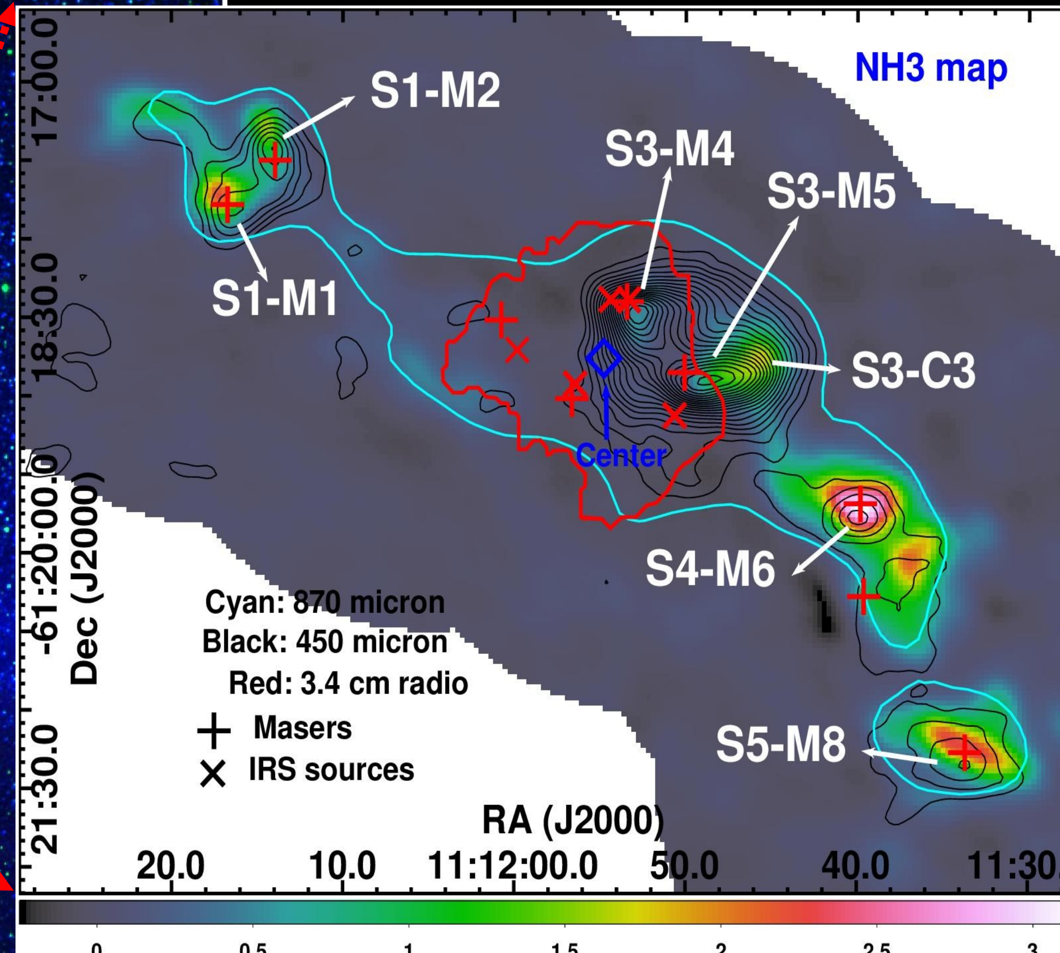




RCW57A: Fragmentation and active star formation



Contours from Purcell+ (2009)

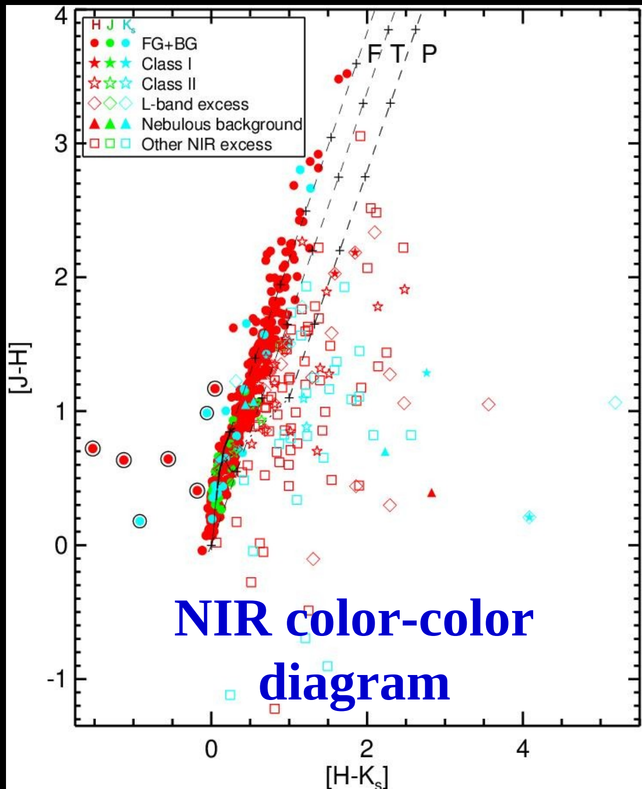


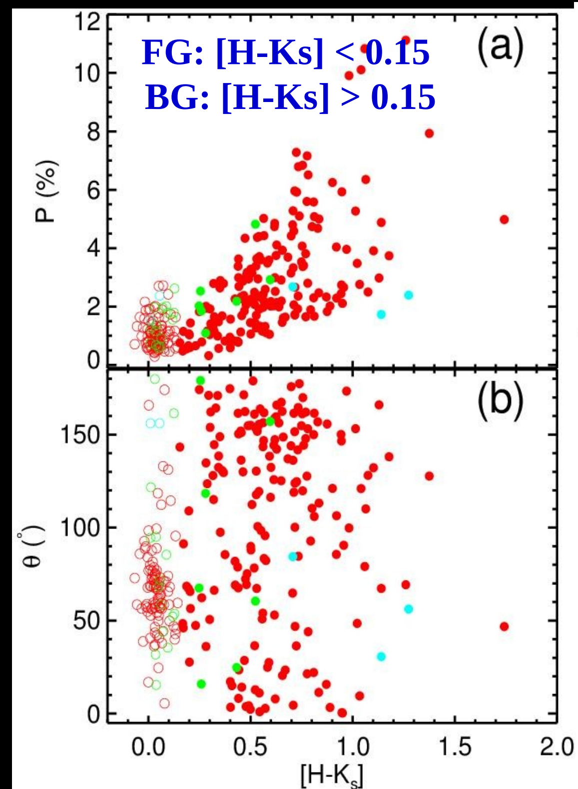
Core	T_d	$M_{core}^{0.35\ pc}$	$M_{env}^{0.03\ pc}$	L_{bol}	$M_{env}/L_{bol}^{0.6}$	T_{bol}	$\langle N_{H_2}\rangle_{0.35\ pc}$	$\langle n_{H_2}\rangle_{0.35\ pc}$
	(K)	$(M_\odot)$	$(M_\odot)$	$(L_\odot)$	$(M_\odot/L_\odot^{0.6})$	(K)	$(10^{23}\ cm^{-2})$	$(10^5\ cm^{-3})$
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
S1-M1	21	250	21	500–10^4	0.1–0.5	$\lesssim$80	1.4	2.0
S1-M2	16	540	45	500–10^4	0.2–1.1	$\lesssim$70	3.0	4.2
S3-M4	35	400	30	0.9–3 $\times10^5$	0.01–0.03	120–170	2.2	3.1
S3-M5	35	460	29	0.5–2.5 $\times10^5$	0.02–0.04	110–160	2.6	3.6
S3-C3	33	490	29	0.5–10 $\times10^4$	0.03–0.2	$\lesssim$60	2.7	3.8
S4-M6	19	350	26	500–10^4	0.1–0.6	$\lesssim$80	2.0	2.7
S5-M8	13.5	500	42	500–10^4	0.15–1.0	$\lesssim$90	2.9	4.0

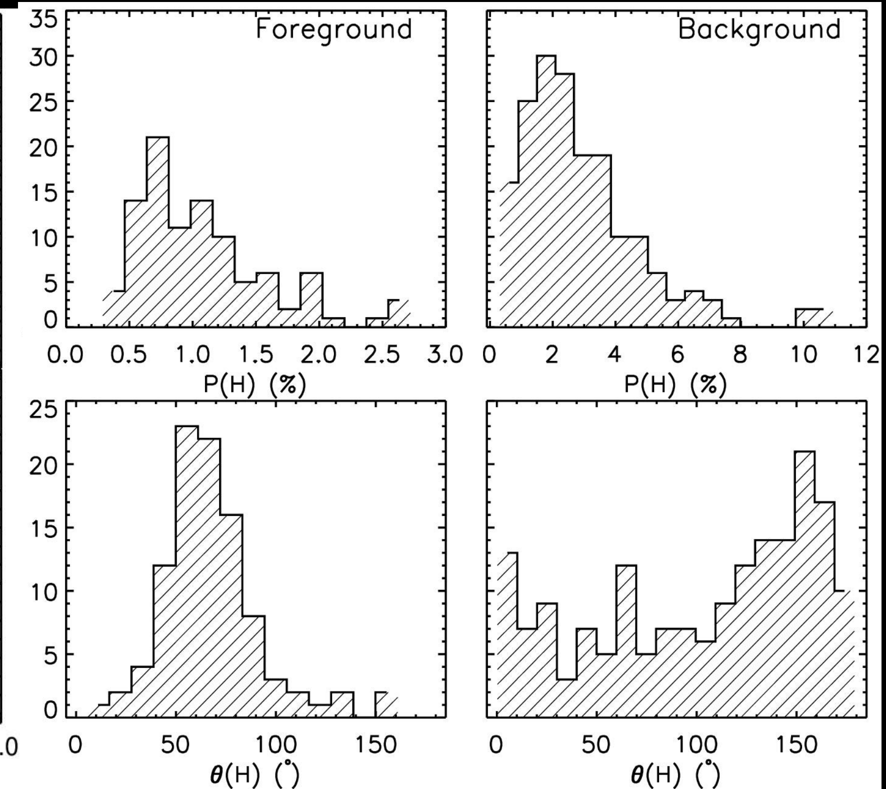
Andre+ (2008)

Still embedded in the molecular cloud, located at 2.4-2.8 kpc

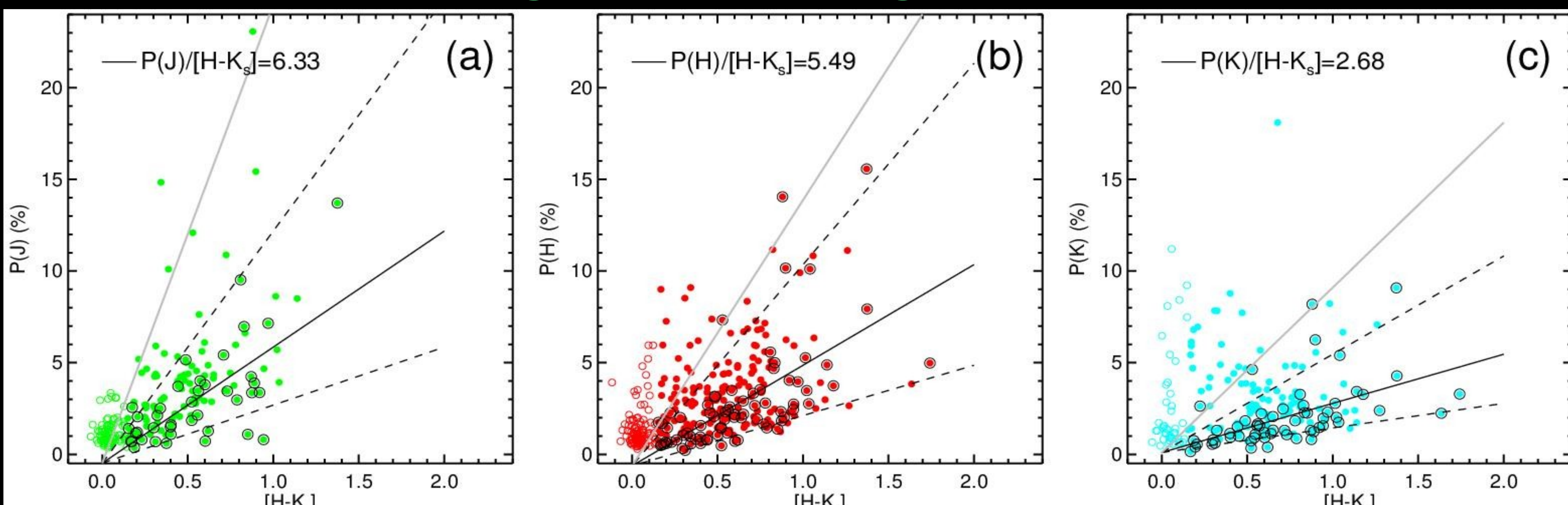
Consist: eight 7.5OV (Persi+ 1994)
more than 130 YSOs, 5 IRS sources,
9 water + methanol masers



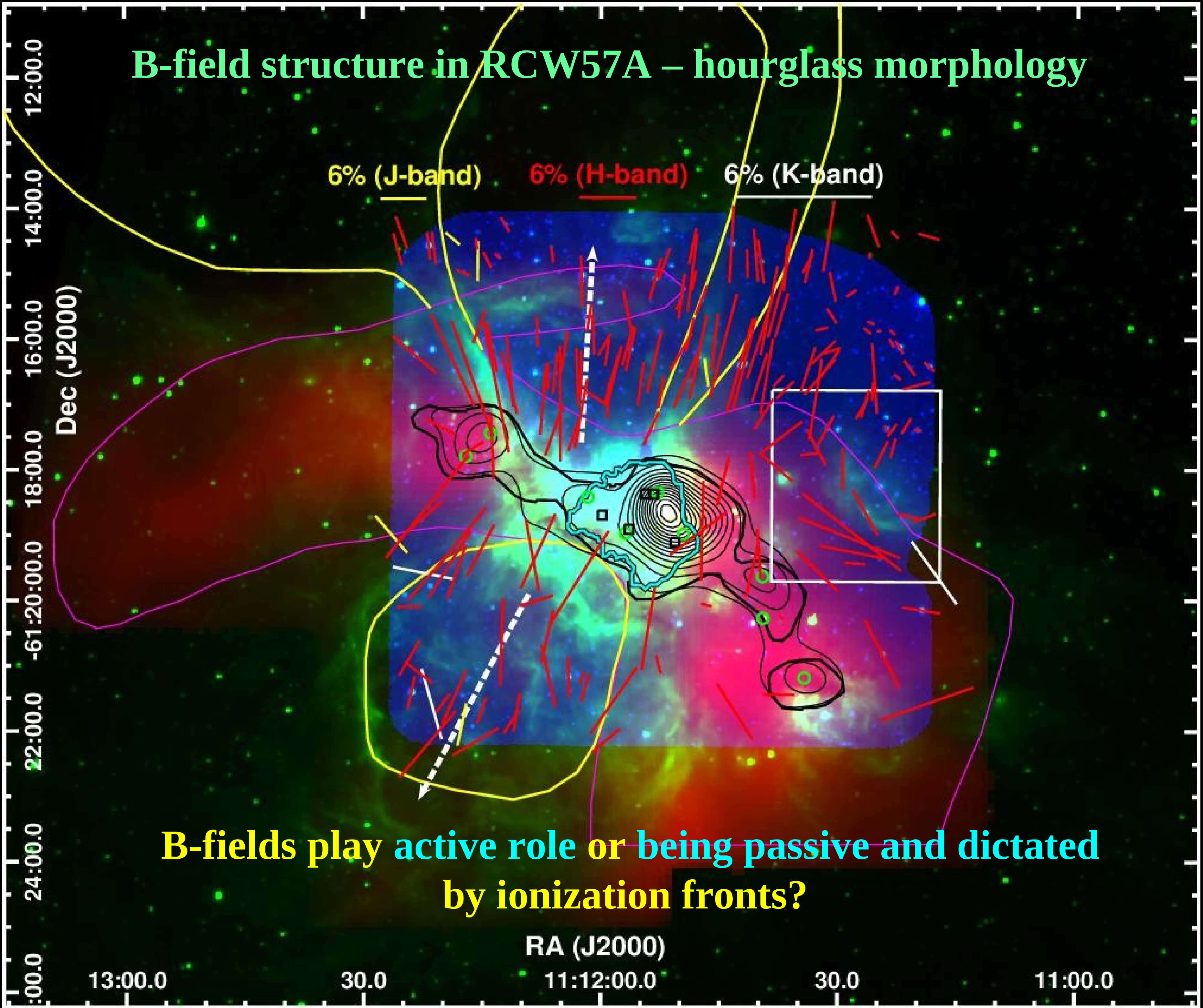




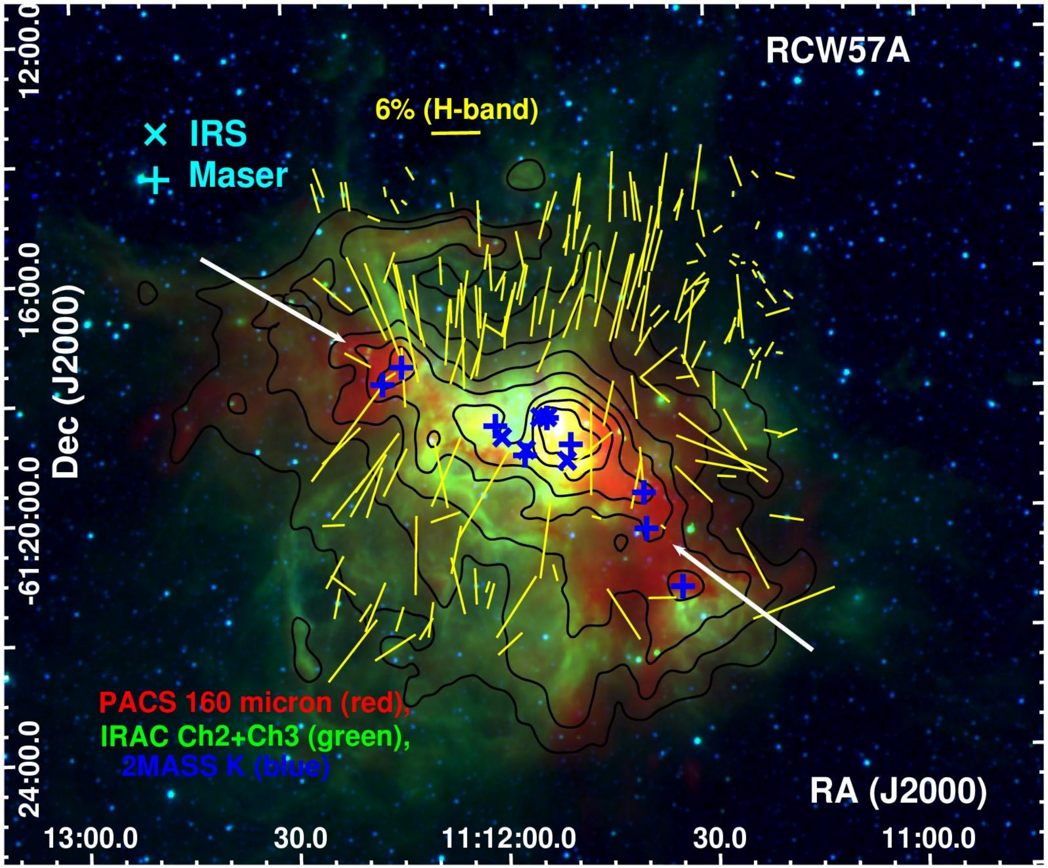
Identification: foreground & background stars, and YSOs



B-field structure in RCW57A – hourglass morphology



B-fields play active role or being passive and dictated by ionization fronts?



B-fields play active role!

$$B = Q\sqrt{4\pi\rho}\left(\frac{\sigma_{V_{LSR}}}{\sigma_{\theta_H}}\right)$$

(Chandrasekhar & Fermi 1953)

Region (1)	B (CF) (μG) (11)
A	84±19
B	67±16
C	69±5
D	95±19
E	56±14

Mean B-field strength: 74±7μG

$$P_B = B^2/8\pi$$

$$P_{turb} = \rho\sigma_{turb}^{\ 2}$$

$$P_{th} \simeq 2n_e k T_e$$

=>n_e, T_e are taken from (Danziger 1974)

=> n_e=22.2 cm^3; Te=9666K

Thermal pressure: 5.93×10^{-11}

Radiative pressure: 2.7×10^{-10}

$$P_{rad} = F/c$$

Region (1)	P_B (dyn cm^{-2}) (2)	P_{turb} (dyn cm^{-2}) (3)	P_B/P_{turb} (4)
A	2.78e-10	6.78e-11	4.1
B	1.80e-10	1.12e-10	1.6
C	1.91e-10	5.64e-11	3.4
D	3.58e-10	1.71e-10	2.1
E	1.26e-10	6.93e-11	1.8

==> $P_B > P_{TURB}$, P_{TH}

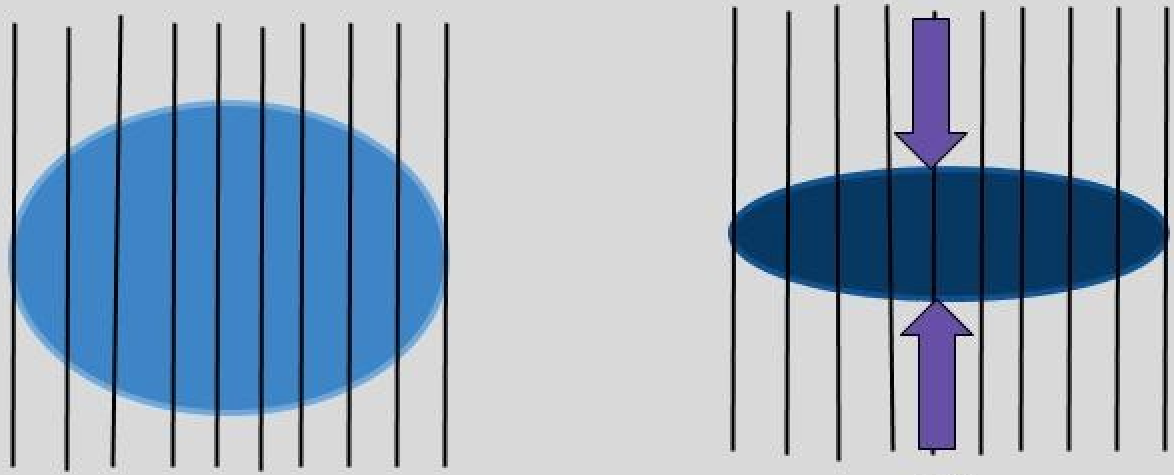
==> $P_B \sim P_{RAD}$ (both act in the same direction)

B-fields play active role!!

=> $P_B \sim 2\, P_{TURB}$

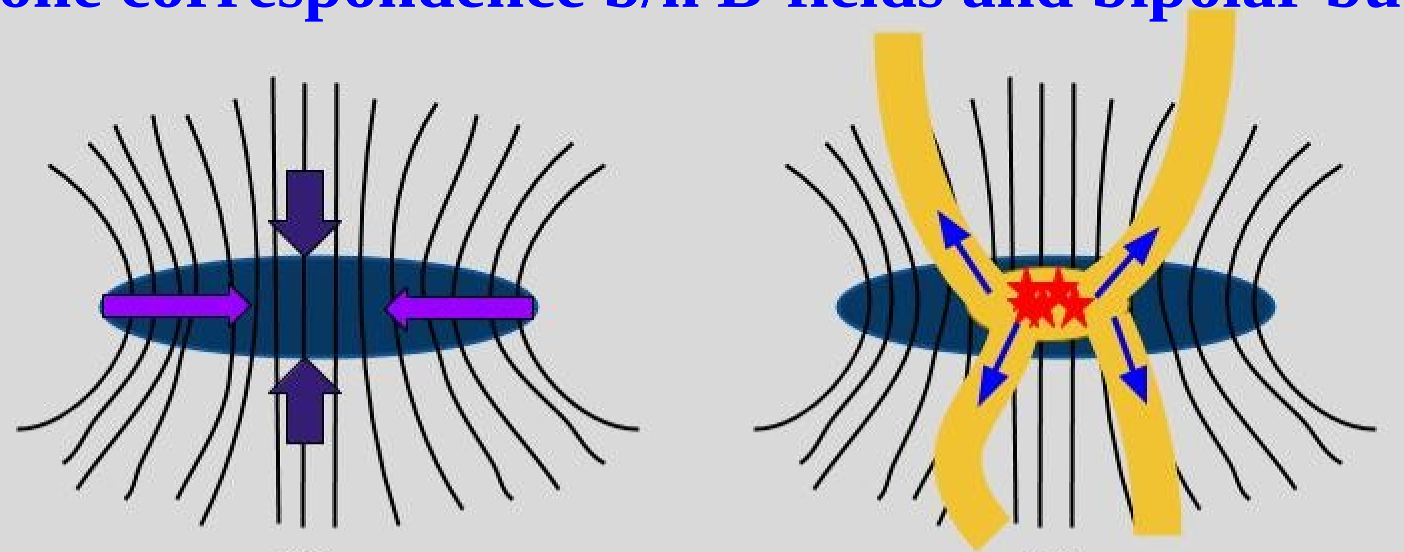
=> Mean B-field pressure: 2.27×10^{-10} (dyn/sq.cm)

Mean turbulent pressure: 9.53×10^{-11} (dyn/sq.cm)



(A) (B)

One-one correspondence b/n B-fields and bipolar bubble



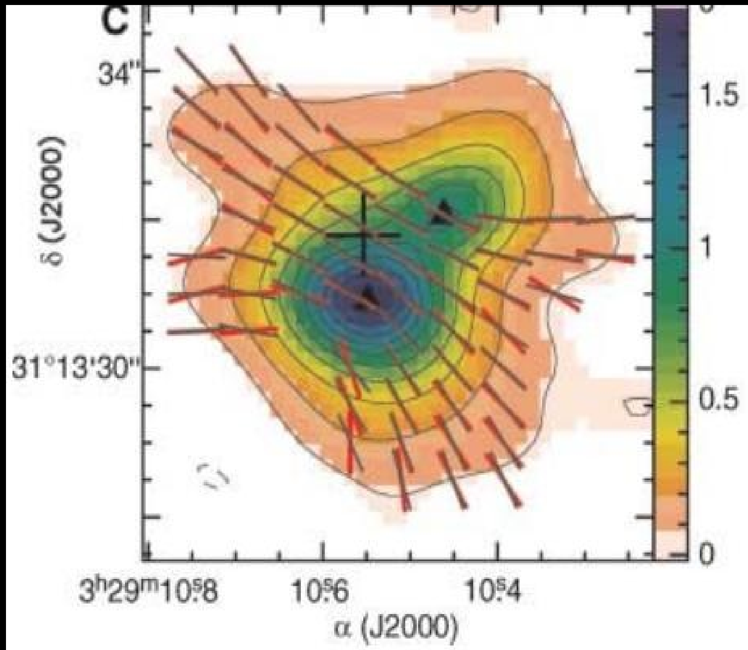
(C) (D)

Schematic diagram - plausible scenario: B-field driven formation and evolution of filament and bipolar bubble

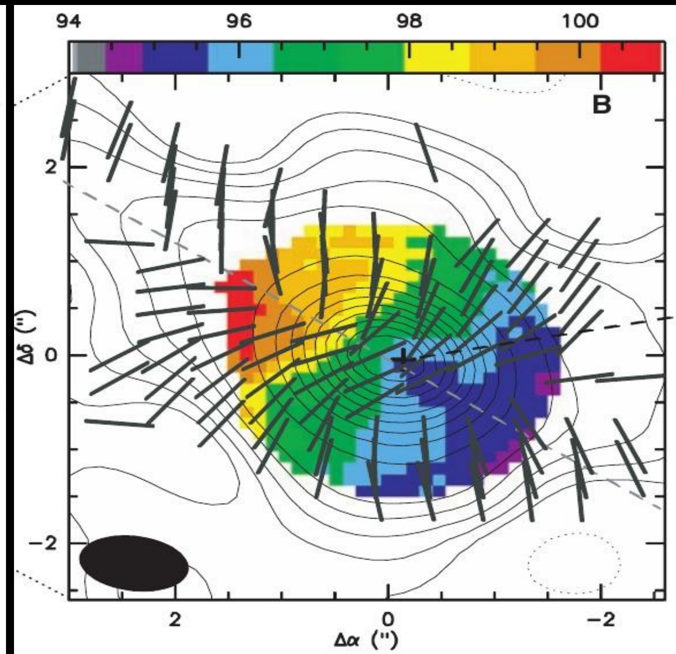
Morphological correlations among filament, bipolar bubble and B-fields in RCW57A: Implications

- **Massive star formation** (B-field guided funneling material flows on to the cores)
- **Cluster formation** (protostellar turbulence and gravitational in flows guided by B-fields)

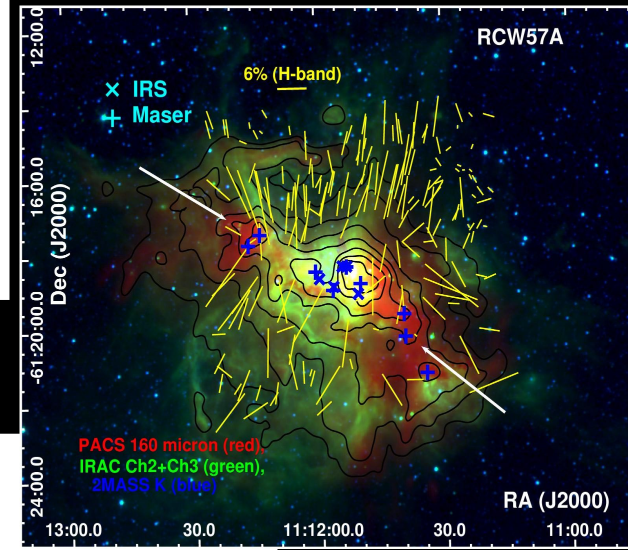
Massive stars form similar to the low-mass stars or by coalescence of multiple cores?

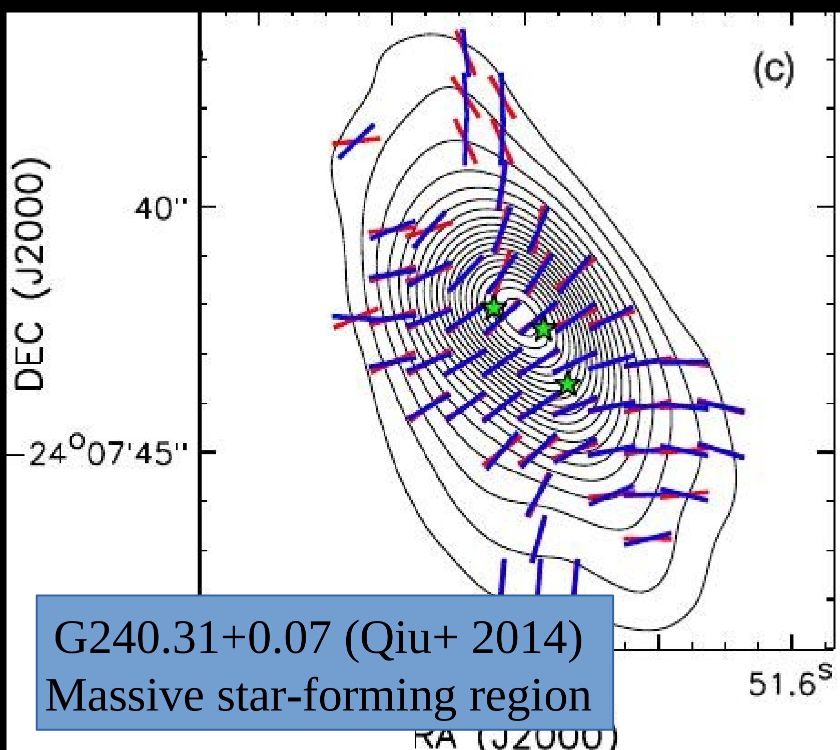


NGC1333 IRAS 4A (Girart+ 2006)
low mass protostellar system

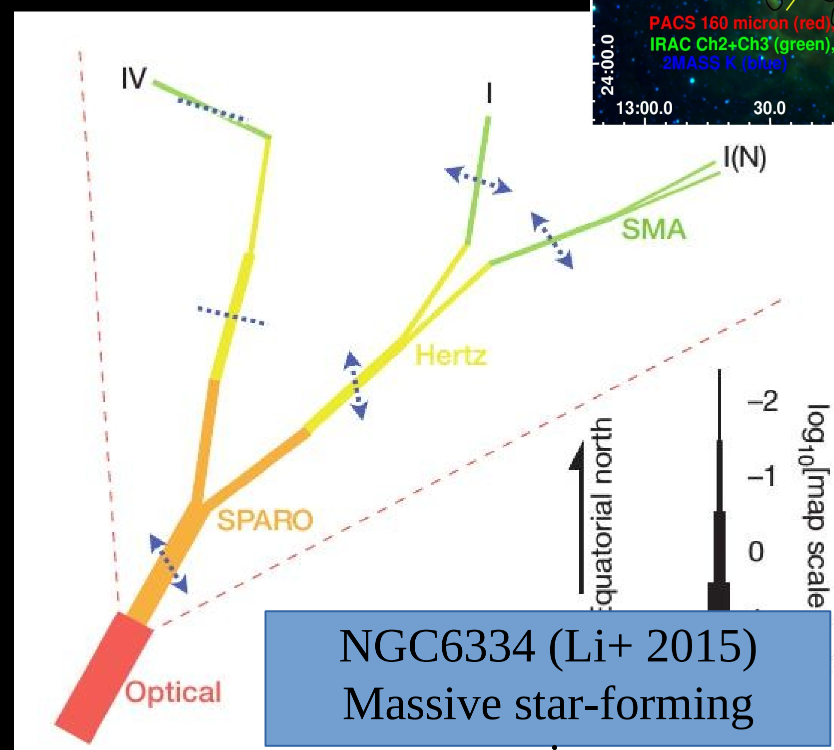


G31.41+0.31 (Girart+ 2006)
high mass molecular clump



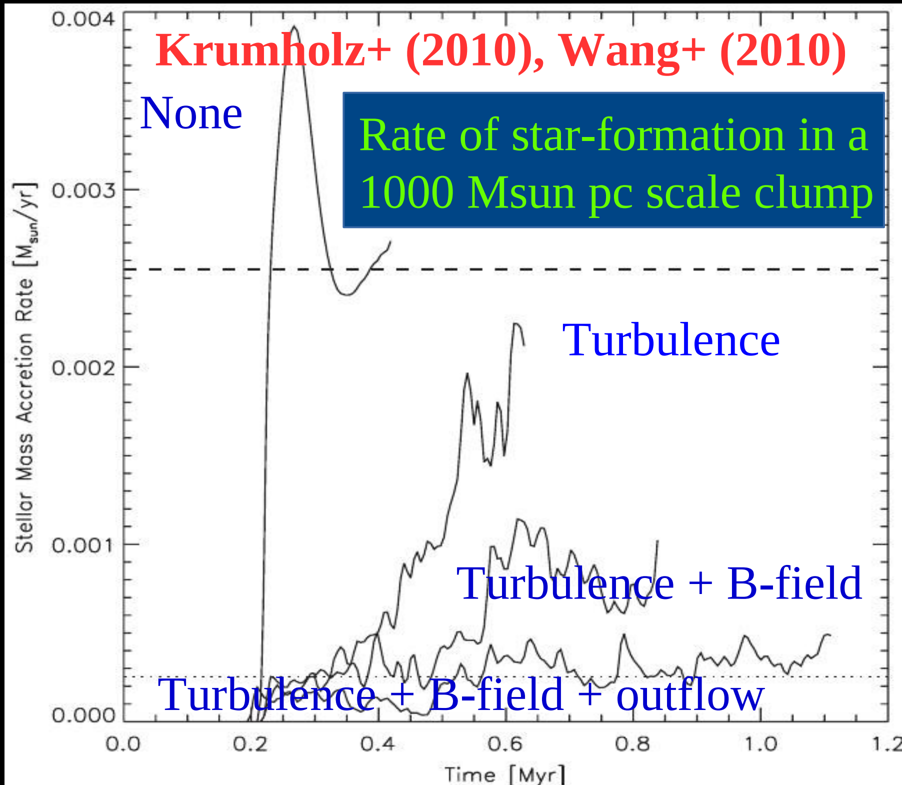


G240.31+0.07 (Qiu+ 2014)
Massive star-forming region



NGC6334 (Li+ 2015)
Massive star-forming region

Outflow regulated **cluster formation**



Most of the stars – in clusters (Lada & Lada 2003)

- 1 pc scale clumps
- 10^2 to 10^3 Msun
- gravity, turbulence and magnetic fields

Possible factors for the low star-formation rate:
Turbulence + B-fields + outflow

-but supersonic turbulence decay rapidly
(~ on turbulence crossing time)
- Therefore, supersonic turbulence should be replenished

Simulations of outflow regulated cluster star-formation:

(I) turbulence dissipation rate > outflow injection rate
(II) kept clump close to virial equilibrium
(III) B-field structure w.r.t cloud structure, and outflows, inflows orientation

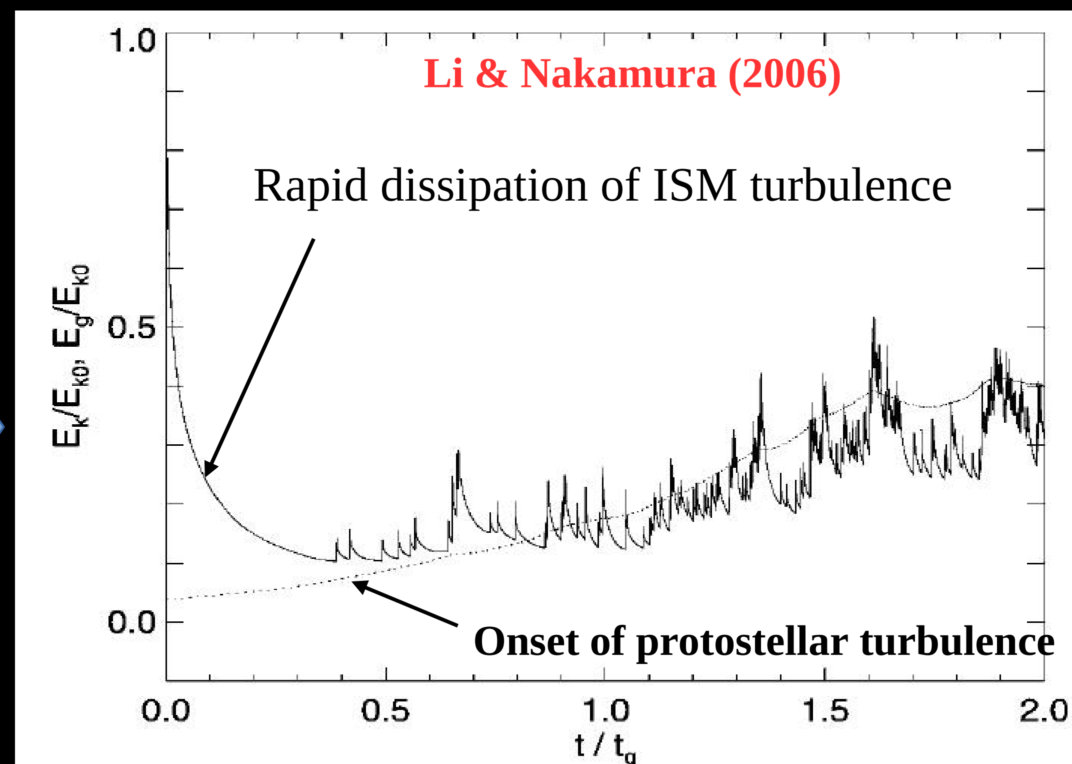


FIG. 1.—Evolution of the total kinetic energy (E_k; *solid curve*) and gravitational energy (E_g; *dotted curve*). The energies are normalized to the initial kinetic energy E_{k0}, and the time to the gravitational collapse time t_g.

Table 3
Observations of Nearby Parsec-scale Cluster-forming Clumps

Name	dP_{turb}/dt ($M_\odot$ km s^{-1} yr^{-1})	dP_{out}/dt[a] ($M_\odot$ km s^{-1} yr^{-1})	$(dP_{out}/dt)/(dP_{turb}/dt)$	P_{out}[b] ($M_\odot$ km s^{-1})	E_{out}[b] ($M_\odot$ km^2 s^{-2})	η_{out}
B59	1.0×10^{-5}	8.5×10^{-5}	8.5	2.6	4	0.62
L1551	1.8×10^{-5}	6.3×10^{-4}	35	19	130	5.0
L1641N	1.3×10^{-4}	1.3×10^{-3}	10	80	273	0.9
Serpens Main	3.4×10^{-4}	2.5×10^{-3}	7.4	75	445	0.27
Serpens South	2.1×10^{-4}	6.5×10^{-4}	3.1	19	165	0.28
ρ Oph	2.9×10^{-4}	1.2×10^{-4}	0.4	3.6	61	0.03
IC 348	2.5×10^{-4}	4.7×10^{-4}	1.9	14	26	0.01
NGC 1333	3.0×10^{-4}	1.1×10^{-3}	3.6	32	119	0.09

(turbulence dissipation)(outflow injection);

Notes.
[a] The outflow momentum injection rates are highly underestimated. See Section 3 for details. The dynamical time of 3×10^4 yr is also adopted to derive the outflow momentum injection rates.
[b] The following two conditions are assumed: (1) the outflow gas is optically thin, and (2) the outflow axes are randomly distributed in the plane-of-sky, and the mean inclination angle of $\xi = 57°3$ is applied for all the outflow components.

Numerical simulations

$dP_{turb}/dt \sim dP_{out}/dt$

dissipation rate ~ injection rate

Clump: Virial equilibrium for a long time

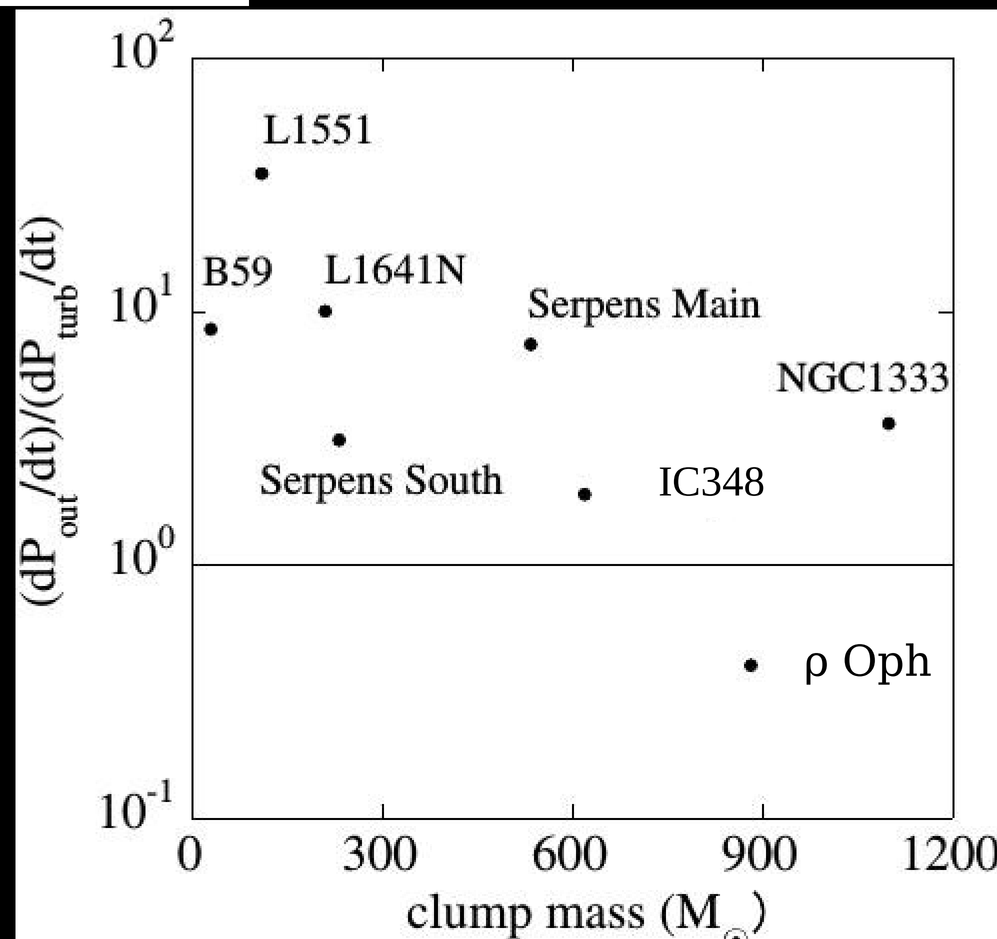
Energy dissipation vs injection rates => outflow feedback to maintain turbulent motions

$$\frac{dP_{turb}}{dt} + \frac{dP_{out}}{dt} = 0$$

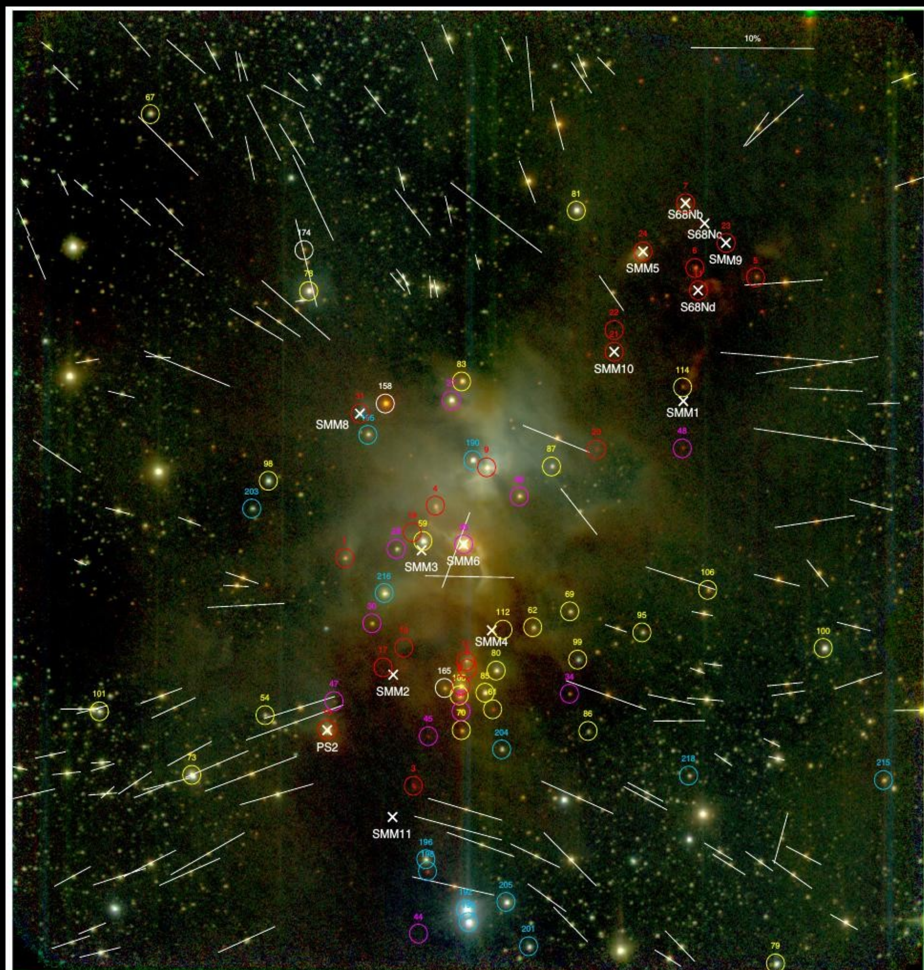
Except ρ Oph outflow momentum injection rate is comparable or larger than the turbulence momentum dissipation rate

Outflows maintain the supersonic turbulence

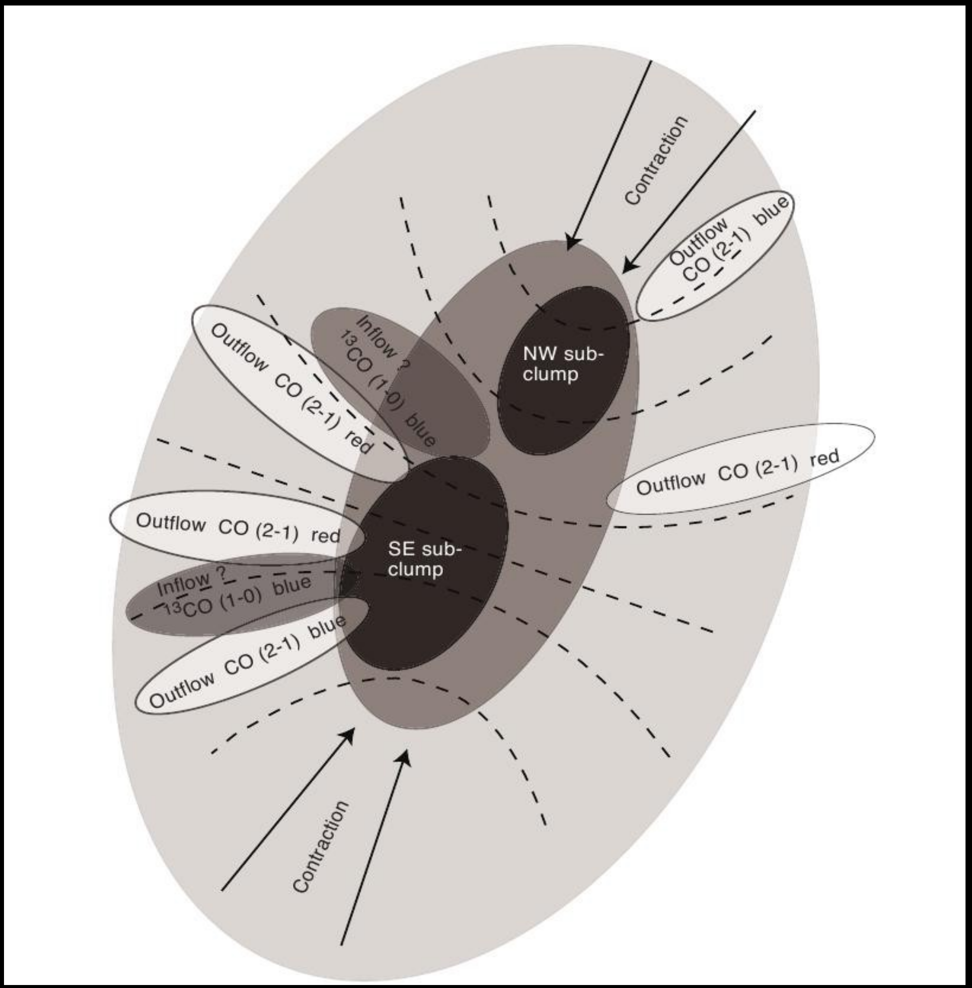
Nakamura & Li (2014)



Expected geometrical correspondence b/n filament, outflows (bipolar bubble) and B-fields according to outflow regulated cluster formation



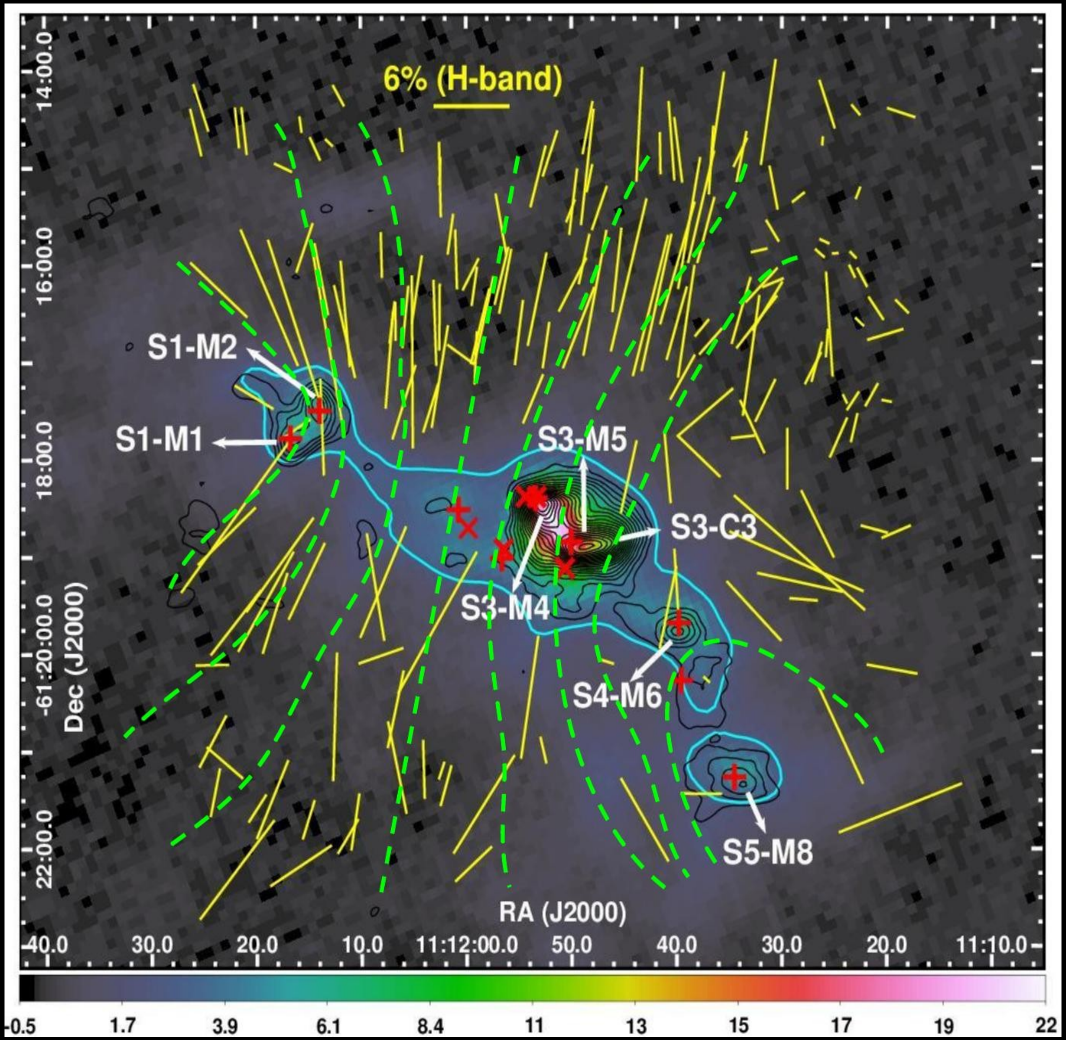
NIR polarization vector map



Schema depicting outflows and inflows

Serpens cloud core (Sugitani+ 2010)

Summary



H-band vectors on 870 micron ATLASGAL map
Black contours: 450 micron P-ArTeMis

- B-fields vs filament and bipolar bubble

- These study traces - pre-existing conditions in favour of massive star and cluster formation

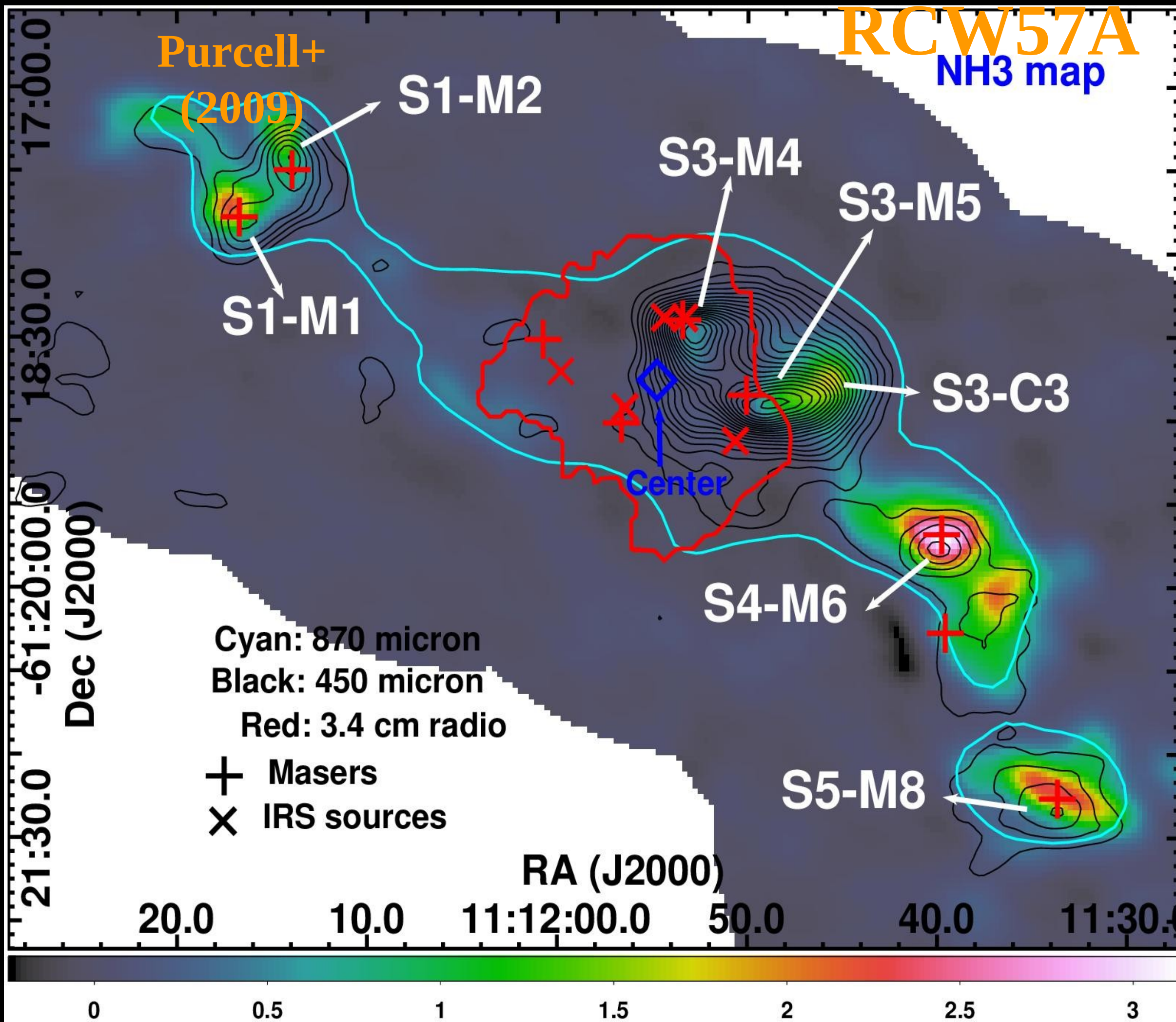
-If B-fields are important in massive star-formation, we expect coherent B-fields upto the clump and core scales.

- B-fields vs cluster formation – via outflow regulated cluster formation

- sub-mm polarimetry at clump-cores scales is essential

Thanks for your kind attention!

Massive stars and cluster in RCW57A



In filament: massive cores & proto stars

- 8 clumps with mass > 250Msun
- massive (> 20 Msun) stars: Class0/I (Andre+ 2008, Purcell+ 2009)

In HII region: cluster

- more than 130 early type YSOs
- at least 8 O7.5V stars (Persi+ 1994)
- yet unrecognized many O-type stars (Townsley 2009)

Core (1)	T_d (K) (2)	$M_{core}^{0.35\ pc}$ ($M_\odot$) (3)	$M_{env}^{0.03\ pc}$ ($M_\odot$) (4)	L_{bol} ($L_\odot$) (5)	$M_{env}/L_{bol}^{0.6}$ ($M_\odot/L_\odot^{0.6}$) (6)	T_{bol} (K) (7)	$\langle N_{H_2}\rangle_{0.35\ pc}$ (10^{23} cm^{-2}) (8)	$\langle n_{H_2}\rangle_{0.35\ pc}$ (10^5 cm^{-3}) (9)
S1-M1	21	250	21	500–10^4	0.1–0.5	$\lesssim$80	1.4	2.0
S1-M2	16	540	45	500–10^4	0.2–1.1	$\lesssim$70	3.0	4.2
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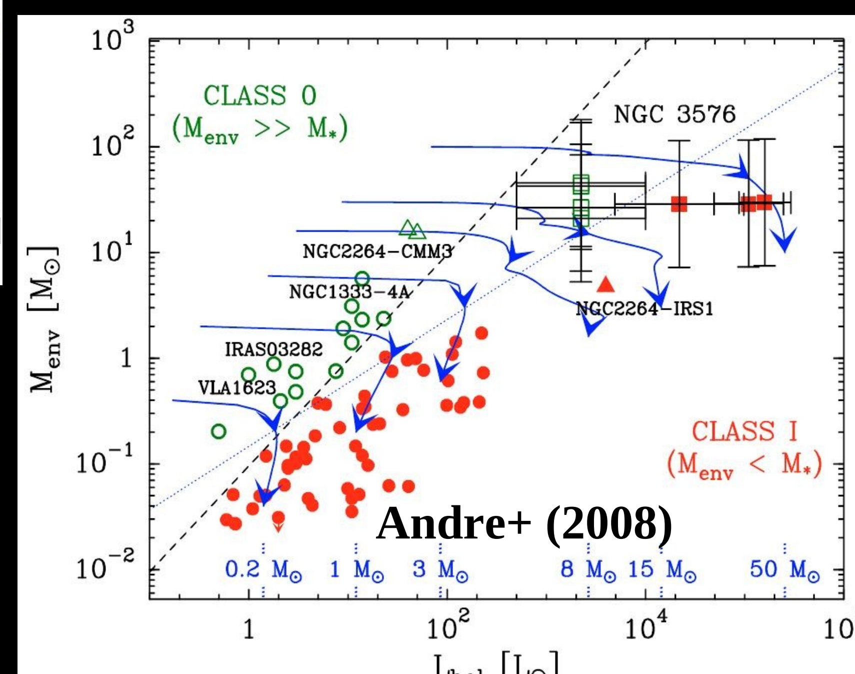
Andre+ (2008)



Massive stars:

- circumstellar disks form via conservation of angular momentum (Terebey+ 1984)
- angular momentum – infalling material – disk growth (York & Bodenheimer 1999)
- accretion of material on the star

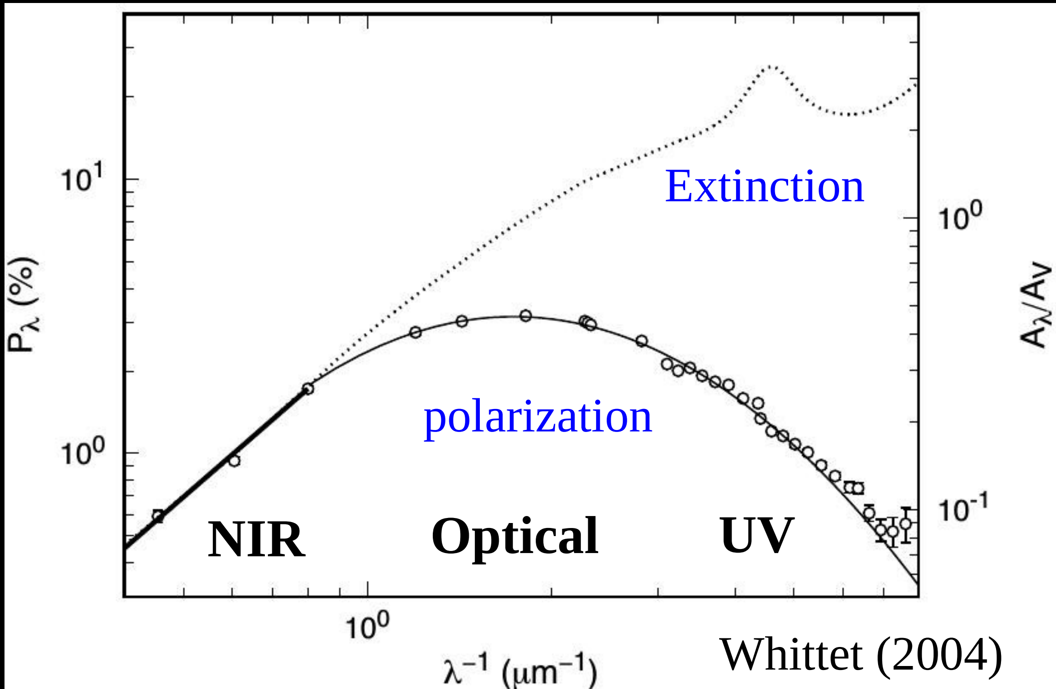
But

- soon after massive star formation – UV raidation quenches further in falling material and accretion (McKee & Tan 2003)
- B-fields can remove angular momentum – by magnetic breaking (Machida+ 2011)
- however massive stars are forming despite of these problems (Patel+ 2005, Zapata+ 2009)

How massive stars form?

- similar to low mass stars? (Giarart+ 2009, Qiu+ 2014)
- colasence of multiple cores – reduced magnetic braking – dynamical interaction – redistribution of angularm momentum (Bonnel & Bate 2002, Zhang+ 2015)
- dissipation of prestellar envelopes (Yen+ 2015)
- misalignment b/n B-field and rotational axis
- turbulence
-ionization degree

Serkowski law – dust size



Optical/UV: $P_\lambda = P_{\max} \exp\{-K \ \ln^2(\lambda_{\max}/\lambda)\}$

NIR $P_\lambda \propto \lambda^{-\beta}$ Where β=1.6-2.0

For background stars: β = 2.22±0.02 and 1.61±0.01 for P(J)/P(Ks), and P(H)/P(Ks), respectively

Foreground dust properties are different from those in the star-forming region

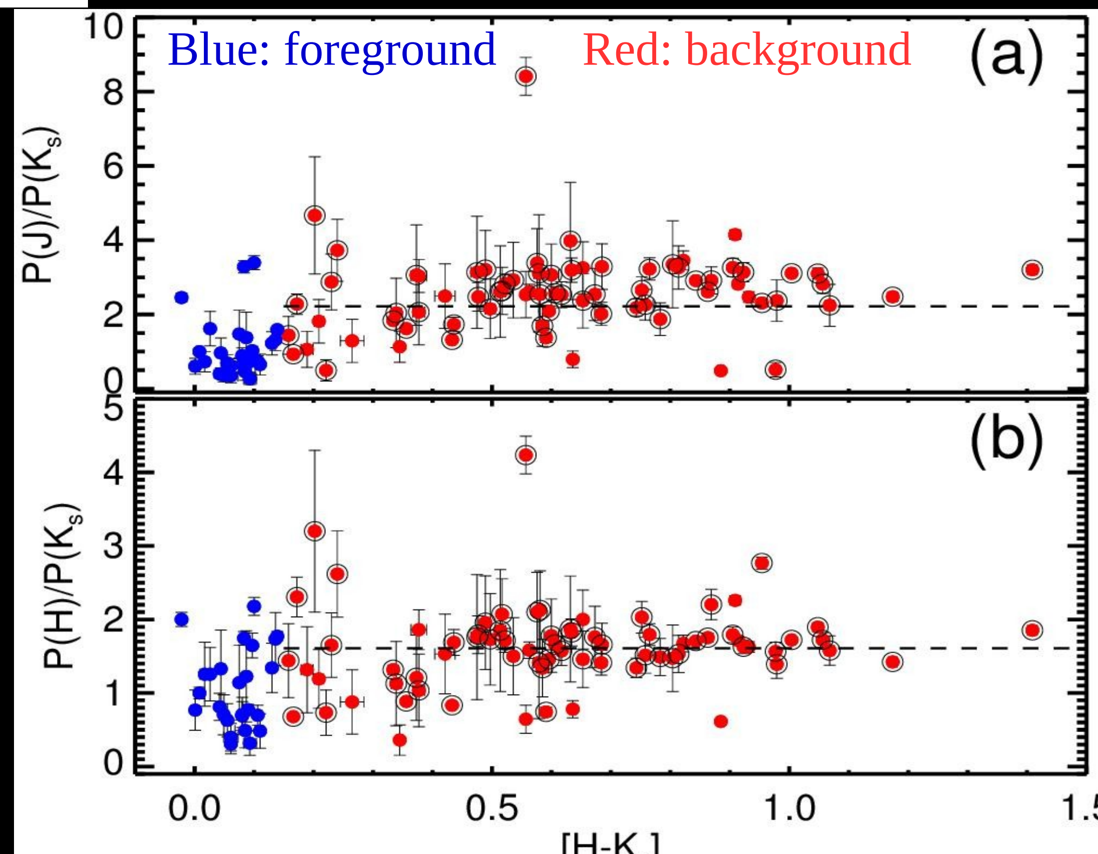


Table 4
Star Formation in Nearby Parsec-scale Cluster-forming Clumps

Name	$N_{\mathrm{Class0/I}}$	$\mathrm{SFR}_{\mathrm{ff}}^{\mathrm{obs}}$ [a] (%)	$\mathrm{SFR}_{\mathrm{ff}}$ [b] (%)
B59	4	7.9	1.3
L1551	3	5.1	1.3
L1641N	14	2.4	2.9
Serpens Main	14	1.9	3.4
Serpens South	42	2.1	4.3
ρ Oph	23	1.3	4.2
IC 348	16	1.8	3.3
NGC 1333	40	6.1	3.0

Notes. The lifetime of protostars is assumed to be 0.4 Myr for all the regions.
[a] $\mathrm{SFR}_{\mathrm{ff}}^{\mathrm{obs}}$ is derived from Equation (13).
[b] $\mathrm{SFR}_{\mathrm{ff}}$ is derived from Equation (10) with $f_B = 1$.

$$\mathrm{SFR}_{\mathrm{ff}}^{\mathrm{obs}} \simeq 0.01 \left(\frac{N_{\mathrm{obs}}}{20}\right) \left(\frac{M_{\mathrm{cl}}}{500\, M_\odot}\right)^{-3/2} \left(\frac{M_*}{0.5\, M_\odot}\right) \times \left(\frac{t_{\mathrm{life}}}{0.4\ \mathrm{Myr}}\right)^{-1} \left(\frac{R_{\mathrm{cl}}}{0.5\ \mathrm{pc}}\right)^{3/2}. \tag{13}$$

M_*:mean protostar mass; t_{life}: life time of Class0/I

$$\mathrm{SFR}_{\mathrm{ff}} \simeq 0.13 a f_B f_{\mathrm{out}} f_{\mathrm{w}}^{-1} V_{\mathrm{w}}^{-1} \frac{G M_{\mathrm{cl}}}{R_{\mathrm{cl}}^2} t_{\mathrm{ff}} = 0.02 \left(\frac{f_B}{0.5}\right) \left(\frac{f_{\mathrm{out}}}{0.3}\right)^{-1} \left(\frac{f_{\mathrm{w}}}{0.4}\right)^{-1} \left(\frac{V_{\mathrm{w}}}{10^2\ \mathrm{km\ s^{-1}}}\right)^{-1} \times \left(\frac{M_{\mathrm{cl}}}{500\, M_\odot}\right)^{1/2} \left(\frac{R_{\mathrm{cl}}}{0.5\ \mathrm{pc}}\right)^{-1/2}. \tag{10}$$

f_B:magnetic support (0-1);

f_{out}: fraction of outflow momentum converted into turbulent momentum

f_{w}:fraction of the outflow contributed as molecular outflows

V_{w}: outflow speed

Nakamura & Li (2014)

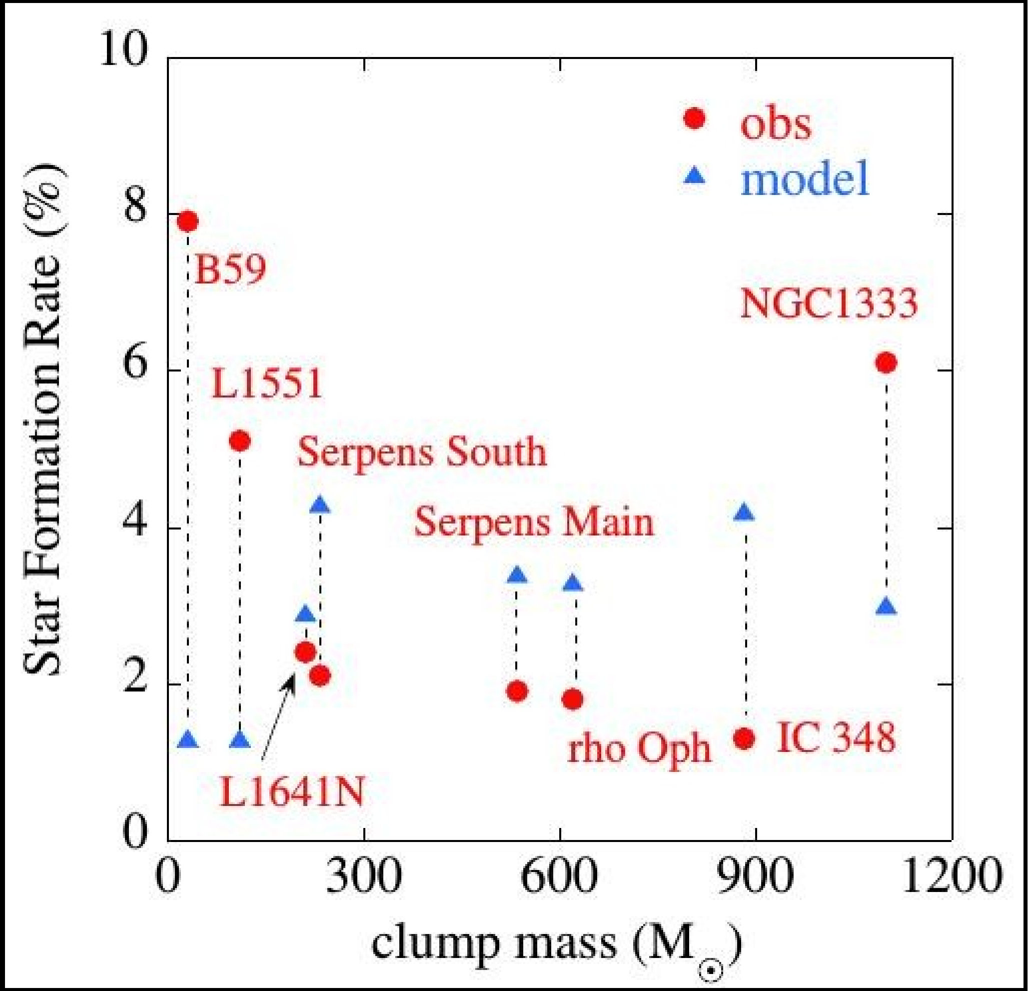
STARFORMATION EFFICIENCY

Slow $\mathrm{SFR}_{\mathrm{ff}}$: few (1-8)%

(life time of Class I: 0.4 Myr)

Rapid $\mathrm{SFR}_{\mathrm{ff}}$: 10%-few x10%

(life of time of Class I: 10^4 yr ~0.01 Myr)



Star-formation rate per free-fall time: observations vs predictions

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Notes.
[a] The outflow momentum injection rates are highly underestimated. See Section 3 for details. The dynamical time of 3×10^4 yr is also adopted to derive the outflow momentum injection rates.
[b] The following two conditions are assumed: (1) the outflow gas is optically thin, and (2) the o
in the plane-of-sky, and the mean inclination angle of $\xi = 57.^\circ 3$ is applied for all the outflow cc

Outflow feedback

Nakamura & Li (2014)

Impact of outflow feedback: Outflows with enough energy disperse surrounding gas
=> quenches further SF ($\eta_{out} > 1$)

$$\eta_{out} \equiv -\frac{2E_{out}}{W}$$

E_{out}: outflow kinetic energy
W:clump gravitational energy

=> η_{out} ~ 0.1 minor role of outflow feedback on global clump dynamics; SF may proceed for a long time