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

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SMA science in the next decade
27-28 Oct 2016
ASIAA
Influence of B-fields on expanding ionization fronts

I-fronts $\Rightarrow$ accelerated

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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)

B-fields provide anisotropic pressure

Filament $\Rightarrow$ HII region $\Rightarrow$ bipolar bubble
(2D HD simulations: Bodenheimer+ 1979; Deherveng+ 2015)
RCW57A: Fragmentation and active star formation

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

<table>
<thead>
<tr>
<th>Core</th>
<th>$T_d$ (K)</th>
<th>$M_{\text{core}}^{0.35}$ pc ($M_\odot$)</th>
<th>$M_{\text{env}}^{0.03}$ pc ($M_\odot$)</th>
<th>$L_{\text{bol}}$ ($L_\odot$)</th>
<th>$M_{\text{env}}/L_{\text{bol}}^{0.6}$ ($M_\odot/L_\odot^{0.6}$)</th>
<th>$T_{\text{bol}}$ (K)</th>
<th>$\langle N_{\text{H}_2}\rangle$ pc (10$^5$ cm$^{-3}$)</th>
<th>$\langle n_{\text{H}_2}\rangle$ pc (10$^3$ cm$^{-3}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1-M1</td>
<td>21</td>
<td>500-10^4</td>
<td>1.1-0.5</td>
<td>&lt;80</td>
<td>1.4</td>
<td>2.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>S1-M2</td>
<td>16</td>
<td>540</td>
<td>0.2-1.1</td>
<td>&lt;70</td>
<td>3.0</td>
<td>4.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>S3-M4</td>
<td>35</td>
<td>400</td>
<td>0.01-0.03</td>
<td>120-170</td>
<td>2.2</td>
<td>3.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>S3-M5</td>
<td>35</td>
<td>460</td>
<td>0.02-0.04</td>
<td>110-160</td>
<td>2.6</td>
<td>3.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>S3-C3</td>
<td>33</td>
<td>490</td>
<td>0.03-0.2</td>
<td>&lt;60</td>
<td>2.7</td>
<td>3.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>S4-M6</td>
<td>19</td>
<td>350</td>
<td>0.01-0.1</td>
<td>&lt;80</td>
<td>2.9</td>
<td>4.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>S5-M8</td>
<td>13.5</td>
<td>500</td>
<td>0.15-1.0</td>
<td>&lt;90</td>
<td>3.9</td>
<td>5.3</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
NIR color-color diagram

Identification: foreground & background stars, and YSOs
B-fields play active role or being passive and dictated by ionization fronts?
B-fields play active role!

\[ B = Q \sqrt{4\pi \rho \left( \frac{\sigma_{V_{LSR}}}{\sigma_{TH}} \right)} \]

(Chandrasekhar & Fermi 1953)

Mean B-field strength: 74±7μG

\[ P_B = \frac{B^2}{8\pi} \]
\[ P_{turb} = \rho \sigma_{turb}^2 \]
\[ P_{th} \sim 2n_e kT_e \]

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

=> \( n_e = 22.2 \text{ cm}^3; T_e = 9666\text{K} \)

Thermal pressure: 5.93x10^{-11}
Radiative pressure: 2.7x10^{-10}

\[ P_{rad} = \frac{F}{c} \]

=> \( P_B > P_{TURB}, P_{TH} \)

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

B-fields play active role!!

<table>
<thead>
<tr>
<th>Region</th>
<th>( P_B ) (dyn cm(^{-2}))</th>
<th>( P_{turb} ) (dyn cm(^{-2}))</th>
<th>( P_B/P_{turb} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>2.78e-10</td>
<td>6.78e-11</td>
<td>4.1</td>
</tr>
<tr>
<td>B</td>
<td>1.80e-10</td>
<td>1.12e-10</td>
<td>1.6</td>
</tr>
<tr>
<td>C</td>
<td>1.91e-10</td>
<td>5.64e-11</td>
<td>3.4</td>
</tr>
<tr>
<td>D</td>
<td>3.58e-10</td>
<td>1.71e-10</td>
<td>2.1</td>
</tr>
<tr>
<td>E</td>
<td>1.26e-10</td>
<td>6.93e-11</td>
<td>1.8</td>
</tr>
</tbody>
</table>

=> \( P_B \sim 2P_{TURB} \)

Mean B-field pressure: 2.27x10^{-10} (dyn/sq.cm)
Mean turbulent pressure: 9.53x10^{-11} (dyn/sq.cm)
One-one correspondence b/n B-fields and bipolar bubble

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 funnelling material flows on to the cores)
- Cluster formation (protostellar turbulence and gravitational in flows guided by B-fields)
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

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

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

-but supersonic turbulence decay rapidly
($\sim$ on turbulence crossing time)
- Therefore, supersonic turbulence should be replenished
Energy dissipation vs injection rates => outflow feedback to maintain turbulent motions

\[
\frac{dP_{\text{turb}}}{dt} + \frac{dP_{\text{out}}}{dt} = 0
\]

Except \(\rho\) 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**

- 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

H-band vectors on 870 micron ATLASGAL map
Black contours: 450 micron P-ArTeMis
Thanks for your kind attention!
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)
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 radiation 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 angular 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: 

\[ P_\lambda = P_{max} \exp\left\{ -K \ln^2(\lambda_{max}/\lambda) \right\} \]

NIR \( P_\lambda \propto \lambda^{-\beta} \) Where \( \beta = 1.6 - 2.0 \)

For background stars: \( \beta = 2.22 \pm 0.02 \) and \( 1.61 \pm 0.01 \) for \( P(J)/P(K_s) \), and \( P(H)/P(K_s) \), respectively.

Foreground dust properties are different from those in the star-forming region.
Star-formation rate per free-fall time: observations vs predictions

**Table 4**

<table>
<thead>
<tr>
<th>Name</th>
<th>N(_{\text{Class0/I}})</th>
<th>SFR(_{\text{ff,obs}}) (^{(%)})</th>
<th>SFR(_{\text{ff,b}}) (^{(%)})</th>
</tr>
</thead>
<tbody>
<tr>
<td>B59</td>
<td>4</td>
<td>7.9</td>
<td>1.3</td>
</tr>
<tr>
<td>L1551</td>
<td>3</td>
<td>5.1</td>
<td>1.3</td>
</tr>
<tr>
<td>L1641N</td>
<td>14</td>
<td>2.4</td>
<td>2.9</td>
</tr>
<tr>
<td>Serpens Main</td>
<td>14</td>
<td>1.9</td>
<td>3.4</td>
</tr>
<tr>
<td>Serpens South</td>
<td>42</td>
<td>2.1</td>
<td>4.3</td>
</tr>
<tr>
<td>(\rho) Oph</td>
<td>23</td>
<td>1.3</td>
<td>4.2</td>
</tr>
<tr>
<td>IC 348</td>
<td>16</td>
<td>1.8</td>
<td>3.3</td>
</tr>
<tr>
<td>NGC 1333</td>
<td>40</td>
<td>6.1</td>
<td>3.0</td>
</tr>
</tbody>
</table>

Notes. The lifetime of protostars is assumed to be 0.4 Myr for all the regions.

\(^{a}\) SFR\(_{\text{ff,obs}}\) is derived from Equation (13).

\(^{b}\) SFR\(_{\text{ff}}\) is derived from Equation (10) with \(f_B = 1\).

**STARFORMATION EFFICIENCY**

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

(life time of Class I: 0.4 Myr)

Rapid SFR\(_{\text{ff}}\): 10%-few x10% 

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

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

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

\[\text{SFR}_{\text{ff}} \approx 0.13 f_B f_{\text{out}} f_w^{-1} V_w^{-1} G M_{\text{cl}} R_{\text{cl}}^2 t_{\text{ff}} \]

\[= 0.02 \left(\frac{f_B}{0.5}\right) \left(\frac{f_{\text{out}}}{0.3}\right)^{-1} \left(\frac{f_w}{0.4}\right)^{-1} \left(\frac{V_w}{10^2 \text{ km s}^{-1}}\right)^{-1} \times \left(\frac{M_{\text{cl}}}{500 M_\odot}\right)^{1/2} \left(\frac{R_{\text{cl}}}{0.5 \text{ pc}}\right)^{-1/2}. \quad (10)\]

\(f_B\): magnetic support (0-1);

\(f_{\text{out}}\): 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)

Star-formation rate per free-fall time: observations vs predictions
Impact of outflow feedback: Outflows with enough energy disperse surrounding gas

=> quenches further SF ($\eta_{\text{out}} > 1$)

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

$E_{\text{out}}$: outflow kinetic energy

$W$: clump gravitational energy

=> $\eta_{\text{out}} \approx 0.1$ minor role of outflow feedback on global clump dynamics; SF may proceed for a long time

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

<table>
<thead>
<tr>
<th>Name</th>
<th>$dP_{\text{turb}}/dt$</th>
<th>$dP_{\text{out}}/dt$</th>
<th>$(dP_{\text{out}}/dP_{\text{turb}})$</th>
<th>$P_{\text{out}}$</th>
<th>$E_{\text{out}}$</th>
<th>$\eta_{\text{out}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>B59</td>
<td>$1.0 \times 10^{-5}$</td>
<td>$8.5 \times 10^{-5}$</td>
<td>8.5</td>
<td>2.6</td>
<td>4</td>
<td>0.62</td>
</tr>
<tr>
<td>L1551</td>
<td>$1.8 \times 10^{-5}$</td>
<td>$6.3 \times 10^{-4}$</td>
<td>35</td>
<td>19</td>
<td>130</td>
<td>5.0</td>
</tr>
<tr>
<td>L1641N</td>
<td>$1.3 \times 10^{-4}$</td>
<td>$1.3 \times 10^{-3}$</td>
<td>10</td>
<td>80</td>
<td>273</td>
<td>0.9</td>
</tr>
<tr>
<td>Serpens Main</td>
<td>$3.4 \times 10^{-4}$</td>
<td>$2.5 \times 10^{-3}$</td>
<td>7.4</td>
<td>75</td>
<td>445</td>
<td>0.27</td>
</tr>
<tr>
<td>Serpens South</td>
<td>$2.1 \times 10^{-4}$</td>
<td>$6.5 \times 10^{-4}$</td>
<td>3.1</td>
<td>19</td>
<td>165</td>
<td>0.28</td>
</tr>
<tr>
<td>$\rho$ Oph</td>
<td>$2.9 \times 10^{-4}$</td>
<td>$1.2 \times 10^{-4}$</td>
<td>0.4</td>
<td>3.6</td>
<td>61</td>
<td>0.03</td>
</tr>
<tr>
<td>IC 348</td>
<td>$2.5 \times 10^{-4}$</td>
<td>$4.7 \times 10^{-4}$</td>
<td>1.9</td>
<td>14</td>
<td>26</td>
<td>0.01</td>
</tr>
<tr>
<td>NGC 1333</td>
<td>$3.0 \times 10^{-4}$</td>
<td>$1.1 \times 10^{-3}$</td>
<td>3.6</td>
<td>32</td>
<td>119</td>
<td>0.09</td>
</tr>
</tbody>
</table>

Notes.

a The outflow momentum injection rates are highly underestimated. See Section 3 for details. The dynamical time of $3 \times 10^4$ 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 is in the plane-of-sky, and the mean inclination angle of $\xi = 57.3$° is applied for all the outflow components.