Dynamical State of The Serpens South Infrared Dark Cloud: From Pre-Protocluster Phase to Protocluster Phase

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I. Introduction

- Most stars form in clusters (Lada & Lada 2003). Therefore, understanding the formation process of star clusters is a key step toward a full understanding of how stars form.
- To elucidate how clusters form, we **observationally characterize the dynamical state of the nearest cluster-forming, infrared dark cloud (IRDC), Serpens South**, which is likely to be in the very early phase of cluster formation.

2. Why Serpens South?

- the nearest (~415pc) cluster-forming IRDC
  spatial resolution ~ 0.04 pc for 20" of NRO 45m
- extremely-high fraction of protostars
  $N_{Class0+I}/N_{Class0+I+II}$ ~ 80 % near the center
- Therefore it is in **very early phase of cluster formation!**

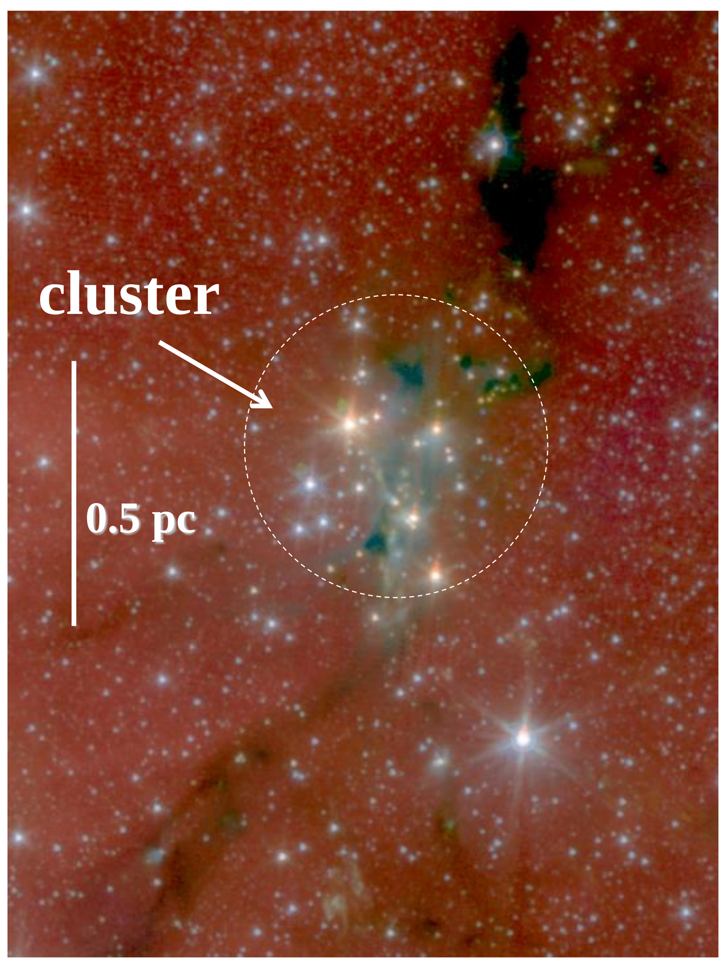

Figure 1. Three-color image of Serpens South with Spitzer IRAC band 1 (3.6 μm, blue), IRAC band 2 (4.5 μmm green), and IRAC band 4 (8.0 μm, red). from Gutermuth et al. (2008)

3. Observations and Data

•Herschel data

PACS 160μm, SIPRE 250, 350, 500 μm

We derived the column density distribution of the Serpens South IRDC from the SED fitting of the Herschel data.

•NRO 45m telescope

N_2H^+ (1-0)
7'x 7' area
25 beam BEARS
OTF mode
Beam size ~ 20"
rms ~ 0.2 K in TA* @ 0.05 km/s

We derived the physical quantities such as velocity dispersion by applying the hyperfine fitting of N2H+.

•SIRPOL on IRSF

Dedicated IR camera on 1.4m telescope in S. Africa
Near-IR 3 band simultaneous polarimetry
J (1.25 micron), H (1.63 micron), Ks (2.14 micron)
Wide-field (7.7'x7.7') with 1" seeing
Deep (all 2MASS sources with 1% Pol. accuracy)

4. Results

Density Distribution --- Fragmentation ---

•The Serpens South IRDC is a filamentary cloud that appears to fragment into several clumps.

•Here, we identified three main clumps with sub-parsec size: northern , central (cluster-forming), and southern clumps.

•The northern clump does not show any active star formation, implying that it is **pre-protocluster clump**.

•The central clump shows active cluster formation, i.e., **cluster-forming clump**.

•Some diffuse filaments appears to converge toward the central dense clump.

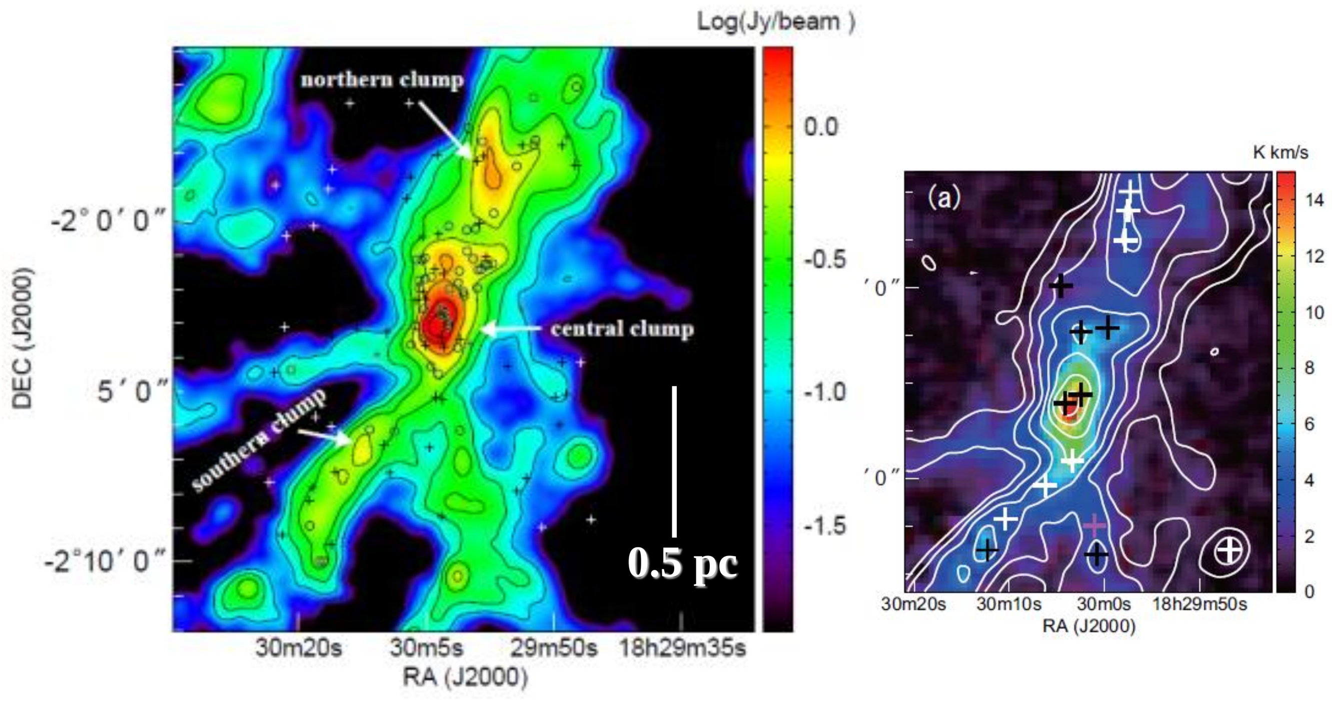

Figure 2. (*left*) AzTEC/ASTE 1.1 mm dust continuum map of Serpens South. The circles and crosses are the positions of Class I and Class II Spitzer YSOs, respectively. The main filament is running from north-west to south-east (See Gutermuth et al. in prep.).
(*right*) N_2H^+ (1-0) velocity integrated intensity map. The contours are the 1.1 mm continuum emission. The black, white, and magenta crosses are the positions of the Herschel starless cores, Class 0 and I sources, respectively..

Magnetic Field --- magnetically regulated? ---

•We performed J, H, and Ks near-infrared polarimetric observations.

•The global magnetic field is spatially well ordered and tends to be perpendicular to the main filament.

•Applying the Chandrasekhar-Fermi method, the strength of the line-of-sight magnetic field is estimated to be about **200 μG**.

•The magnetic field is likely to play an important role in the dynamical evolution of the filament.

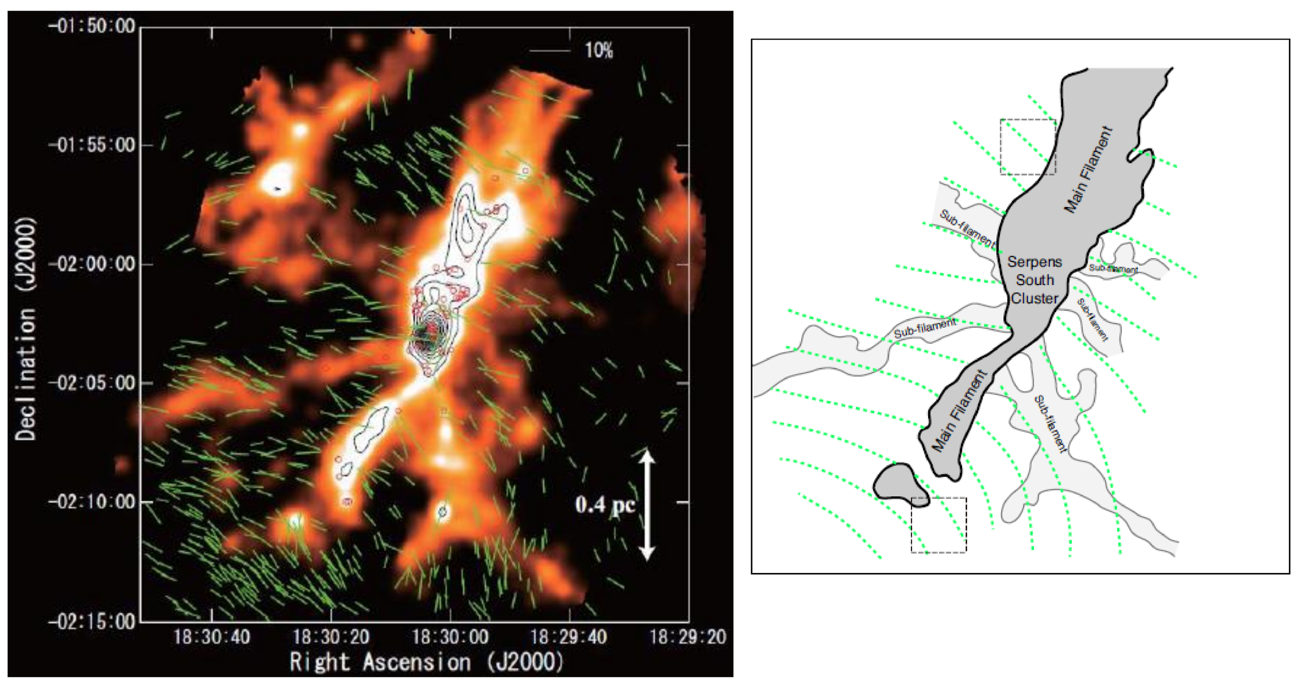

Figure 3. (*upper*) H-band polarization vector map toward Serpens South for point sources having P/ΔP > 3.0,P < 6.6([H − Ks] − 0.2), and P > 3.0%, superposed on the 1.1-mm dust-continuum image of ASTE/AzTEC (Gutermuth et al. 2013, in prep.).
(*bottom*) Schematic drawing of the main and sub-filaments of the Serpens South cloud. The outlines of the filaments and the magnetic field lines are shown by black lines and green dotted lines, respectively.

5. Virial Analysis

We apply the virial analysis to the three clumps.

virial equation

$$\frac{1}{2}\frac{\partial^2 I}{\partial t^2} = 2U + W$$

$$U = \frac{3M\Delta V^2}{16\ln 2}$$

$$W = -a\frac{GM^2}{R}\left[1-\left(\frac{\Phi}{\Phi_{cr}}\right)^2\right]$$

PHYSICAL QUANTITIES OF CLUMPS IN SERPENS SOUTH

Physical Quantities	Serps N	Serps C	Serps S
Mass ($M_\odot$)	193	232	36
Radius (pc)	0.189	0.200	0.093
ΔV (km s^{-1})	0.665	1.25	0.580
U ($M_\odot$ km^2 s^{-2})	36	114	5.7
W ($M_\odot$ km^2 s^{-2})	−721	−1000	−43.6
α_{vir}	0.10	0.23	0.26
Γ [a]	1.5	1.6	1.1

[a] the mass-to-magnetic flux ratio normalized to the critical value $2\pi G^{1/2}$.

•The northern and central clumps have similar masses.

•The central, cluster-forming clump has a larger line width, presumably due to protostellar outflow feedback.

•All the three clumps have small virial ratios, indicating that the internal turbulence alone cannot support the clumps against gravity.

•However, the clumps do not undergo rapid free-fall collapse whose line width is expected to be around 3-4 km/s.

•The magnetic field estimated from the C-F method (nearly magnetically-critical field) provides significant support against gravitational collapse.

6. Scenario of Cluster Formation

(a) Fragmentation of a filamentary cloud.
The fragmentation is likely to be driven by ambipolar diffusion.

(b) pre-protocluster phase
The clumps grow in mass by gas accumulation. The merging of the fragments along the filament axis may also play a role in increasing the clump mass.

(c) Cluster formation is initiated and protostellar outflows start injecting supersonic turbulence in the clumps.

(d) Eventually, the clump reaches quasi-virial equilibrium due to protostellar outflows.

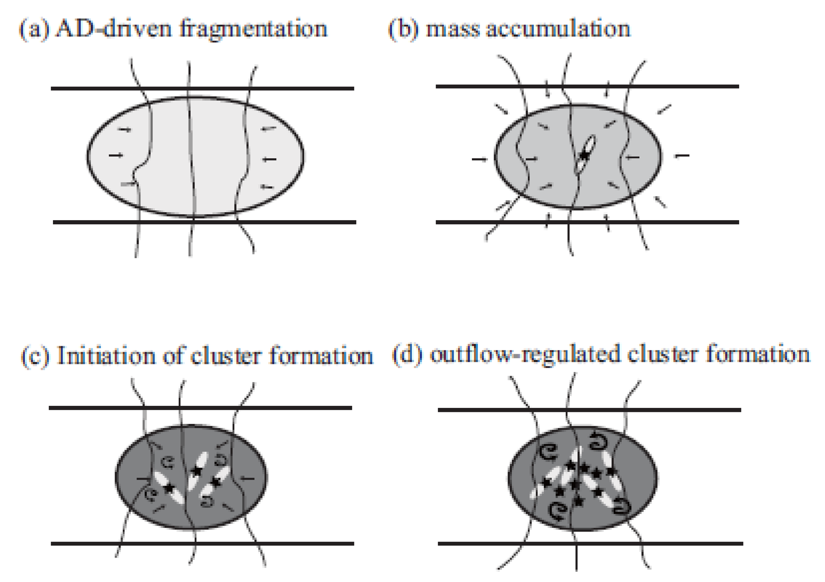

Figure 4. Magnetically-Regulated Cluster Formation in Serpens South

7. Summary

- We found several sub-parsec-scale dense clumps in different evolutional stages: pre-protocluster and protocluster clumps.
- **The pre-protocluster clump** has cold and small line width, and thus **small virial ratio**, presumably supported by the strong magnetic field that prevents the rapid global contraction.
- **The protocluster clump** has a virial ratio that is larger than that of the pre-protocluster clump, presumably due to the protostellar outflow feedback.
- **We propose that the cluster formation in Serpens South is likely to be controlled by the magnetic field.**

REFERENCES

1. **Protostellar Outflow:** Nakamura, F., Sugitani , K., Shimajiri, Y. et al. *The Molecular Outflows From the Protocluster, Serpens South*, 2011, ApJ, 737, 56
2. **Magnetic Field:** Sugitani , K., Nakamura, F., Watanabe, et al. *Near-IR Polarimetry toward Serpens South: Revealing the Importance of the Magnetic Field*, 2011, ApJ, 734, 63
3. **Dynamical State:** Tanaka , T., Nakamura, F., Awazu, Y. et al. *The Dynamical State of the Serpens South Filamentary Infrared Dark Cloud*, 2013, submitted to ApJ