VLA Radio Observations Reveal Embedded Protostars in the Serpens South Infrared Dark Cloud

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1. Abstract

The earliest stages of star formation are obscured at optical and infrared wavelengths due to the thick envelopes that surround protostars during the pre-stellar, Class 0 and Class I phase. Radio observations that can penetrate the envelope's high optical depth have therefore proven to be an indispensible tool for studying these early stages[1]. Radio observations allow us to discriminate between the pre-stellar and Class 0 phase through the detection of a compact central source[1]; they allow us to study radio jets that are thought to be indicative of large-scale outflows[2], and are beginning to shed light on the long-standing issue behind very low luminosity objects (VeLLOs) with higher sensitivity observations[3].

Discovered in 2008, Serpens South was found to harbor an unusually high ratio of Class I to Class II protostars (~80%) , which is the highest among infrared dark clouds within 400 pc, suggesting it is in a very early phase of cluster formation[4]. Here, we present deep radio observations at 4.1 and 6.3 cm towards the Serpens South Infrared Dark Cloud in an attempt to better characterize the clustered star formation taking place in the core of its central filament, see Figure 1. We detect 18 radio sources, of which, 5 to 8 are likely protostellar in nature. Of these protostellar candidates, 1 to 2 are newly discovered embedded Class 0 protostars. We also detect candidates for possible radio jets and two VeLLOs. Beyond our 18 confident detections, we weakly detect another 5 protostellar candidates, suggesting that higher sensitivity observations will yield further protostellar detections.

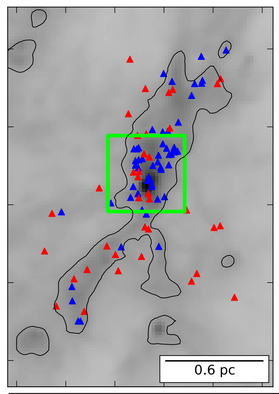

Figure 1 above: Serpens South IRDC and our field of view on its central filament.

2. Observations & Data

We utilized the VLA in its C configuration to observe Serpens South for 1 hour on July 2nd, 2013. We observed in two bands centered at 4.1 cm (7.25 GHz) and 6.3 cm (4.75 GHz) with bandwidths of 1.024 GHz. We focused on a 3.5 x 3.5 arcminute region around the central filament (Figure 1). Table 1 below outlines our resolution and sensitivity.

We also cross-referenced 2MASS catalogues and ran source extractions over Spitzer IRAC & MIPS and Herschel PACS images to produce a multiwavelength dataset of star formation in Serpens South's central filament from 1 μm to 70 μm.

Wavelength (cm)	Beam Size[a] (arcsec x arcsec)	Position Angle (degrees)	Image RMS (μJy beam^{-1})
6.31	4.8 x 3.9	13.4	11.1
4.14	3.2 x 2.5	12.7	8.5

[a] Deconvolved with robust weighting, *robust*=0.5 (Briggs 1995).

3. Results: Fragmentation of Molecular Gas into Compact Sources

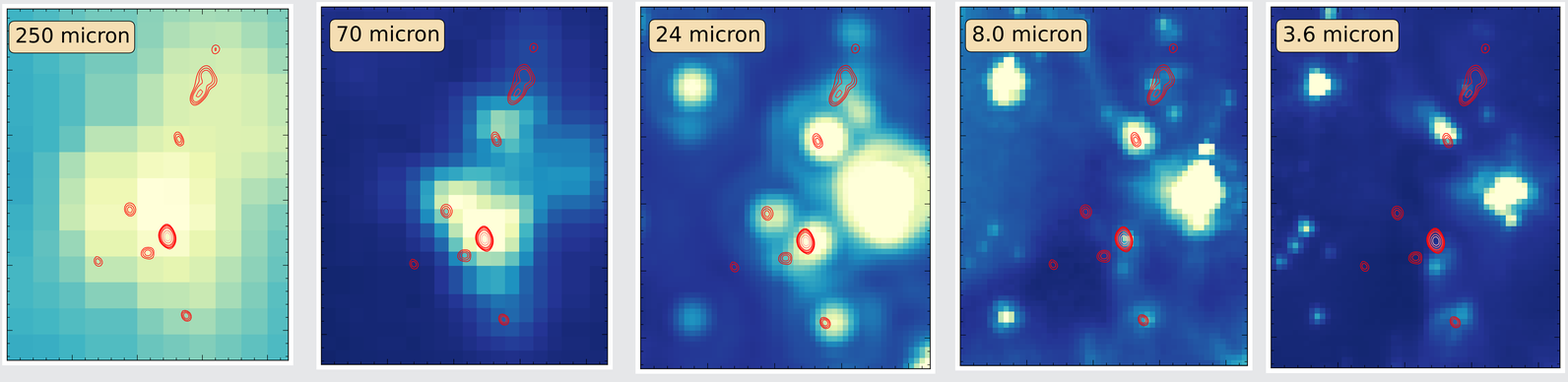

Figure 2 shows how the cold dust traced by sub-mm emission longward of 250 μm neatly encompasses our radio sources, but cannot resolve individual compact sources. Shorter wavelengths around 3.6 μm tracing heated dust give more accurate spatial positions and detect high numbers of Class I and II candidates, but are blind to young and embedded sources. By detecting up to two new embedded Class 0 candidates and giving more accurate positions of other embedded protostars, our work gives a clearer picture as to how the highly clustered molecular gas fragments into compact young stellar objects.

Figure 2 above: VLA 4.1 cm radio contours plotted over SPIRE, PACS, MIPS and IRAC images of Class 0, I and II protostars at the core of Serpens South's central filament. Radio contours start at the 4-sigma level.

This will benefit further studies that aim to deduce how gas clumps form into Class 0 protostars; we have, for example, already shown that at least three Class 0 can live inside one broad millimeter emission peak. This work also sheds light on how protostars are formed under the influence of a highly clustered environment--within an angular separation of 30 arcseconds (0.06 pc) we detect four embedded protostars, two of which are candidates for driving large scale outflows, see Figure 3. Anything else I should say?

4. Discussion: Outflows, VeLLOs and more

Outflows:

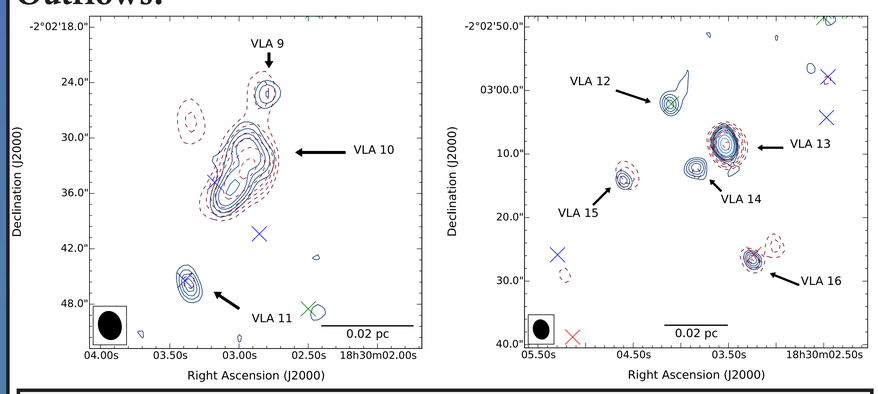

Figure 3 above: Radio contour images of protostellar candidates. Blue solid contour and red dashed contour correspond to 4.1 and 6.3 cm images respectively. Blue and red crosses indicate Spitzer identified Class I and II protostars, respectively, while green crosses indicate millimeter emission peaks. Beam size at lower left represents 4.1 cm resolution. **At left:** Radio contour image of VLA 9, 10 and 11. **At right:** Radio contours of VLA 12, 13, 14, 15 and 16.

Early radio studies showed that at high resolutions, protostellar radio sources are generally found to be elongated[2]. This elongation follows the direction of large-scale molecular outflows and is thought to represent the base of jets that shock the protostellar envelope[3]. Teixeira et al. 2012 conducted a H_2 v = 1–0 S(1) 2.122 μm study to characterize jets and outflows in Serpens South[5]. Within our field of view, they identify three protostars as candidates for drivers of outflows. We detect strong radio emission from two of their candidates, both of which exhibit elongation in the direction of Teixeira et al. 2012's quoted outflow direction. Both of these candidates are Class 0 protostars, which supports the notion that young stellar objects can drive powerful outflows even in their infancy.

Very Low Luminosity Objects (VeLLOs):

A VeLLO is defined as a protostar with an internal luminosity less than 0.1 L_{SUN}. Dunham et al. 2008 found a tight correlation between PACS 70 μm emission and internal luminosity. Where possible, we use this to estimate the internal luminosity of our protostellar sources. We find that two of our sources have internal luminosities at or below 0.1 L_{SUN} within their errors. VeLLOs represent a whole new area of protostars that have been largely unstudied due to technological constraints. Their continued detection and study will allow us to determine the lower limit to protostellar formation.

Radio Flux vs. Bolometric Luminosity:

A correlation between radio flux and bolometric luminosity has shown to exist at centimeter wavelengths[2, 6]. Shirley et al. 2007 compiled a decade's worth of radio observations and presented an updated relationship for radio flux at 3.6 cm and 6.0 cm (Figure 4). Because of the highly clustered nature of our protostars, millimeter observations cannot determine the bolometric luminosities of our protostars on an individual basis. Therefore, we turn to our infrared dataset and use infrared luminosity-to-bolometric luminosity relationships defined by Kryukova et al. 2012 and Dunham et al. 2013. For five sources with relatively complete infrared associations, we find relative agreement with our protostars and Shirley et al. 2007's relationship, although our Lbol errors are quite large.

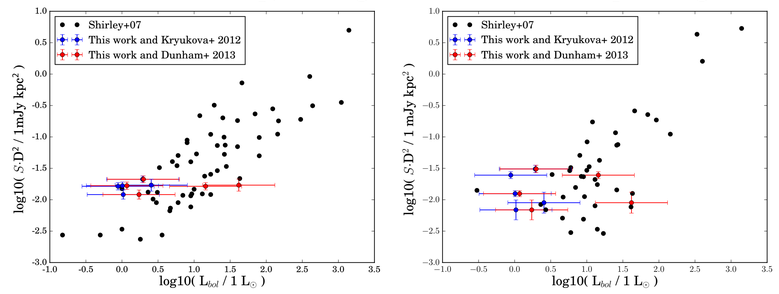

Figure 4 above: Relationship between protostellar radio flux and bolometric luminosity. Blue data represents Lbol estimated from Kyrukova et al. 2012's Lmir to Lbol relationship, while red represents Dunham et al. 2013's relationship.. **Left:** 3.6 cm flux vs. bolometric luminosity. **Right:** 6.0 cm flux vs. bolometric luminosity.

Summary

- We present deep radio observations of Serpens South's highly clustered central filament with the VLA at 4.1 and 6.3 cm.
- We detect up to roughly eight protostellar radio sources and find up to two new embedded Class 0 protostars. We find two sources that exhibit radio jet morphology, and two sources that can be classified as a VeLLOs.
- With a multiwavelength data set, we compare our protostellar radio fluxes to the known radio flux vs. bolometric luminosity relationship and find relative agreement.
- Our study motivates further higher sensitivty and higher resolution radio observations of Serpens South to detect more embedded protostars and resolve radio jets.

Acknowledgements & References

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