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, for example, allow us to discriminate between a pre-stellar and young stellar object through the detection of a compact central source[1], and allow us to study radio jets that are thought to be related to large-scale outflows and protostellar accretion[2].

Discovered in 2008, Serpens South was found to harbor an unusually high ratio of Class I to Class II protostars (~80%), 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 its central filament (Figure 1). We detect 18 radio sources, of which, five to eight are likely protostellar in nature. Of these candidates, one to two are newly discovered embedded Class 0 protostars. Beyond our confident protostellar detections, we weakly detect another five protostellar candidates, suggesting that higher sensitivity observations will yield further protostellar detections. Additionally, we use our radio images to deduce the prescence of radio jets and compare our fluxes to the radio vs. bolometric lumionsity correlation.

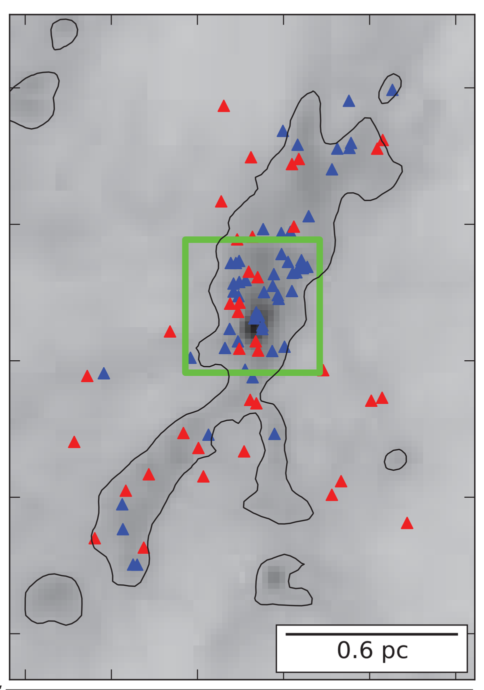

Figure 1 above: Serpens South IRDC and our field of view on its central filament.

2. Observations & Data

We utilized the VLA in its C configuration for 1 hour on July 2nd, 2013. We used two bands centered at 4.1 cm (7.25 GHz) and 6.3 cm (4.75 GHz) with 1.024 GHz bandwidths. Our region-of-interest was a 3.5 x 3.5 arcminute region around the central filament (Figure 1).

We also cross-referenced 2MASS catalogues and ran source extractions over Spitzer IRAC & MIPS and Herschel PACS images to produce a multiwavelength dataset from 1 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

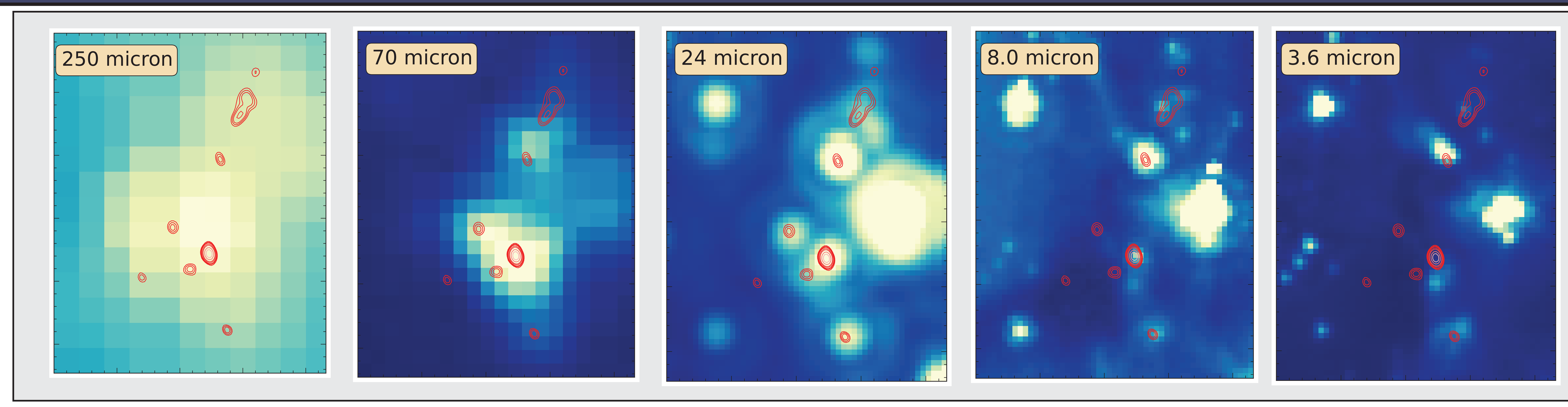

Figure 2: VLA 4.1 cm radio contours of 8 out of our 18 radio sources plotted over SPIRE, PACS, MIPS and IRAC images of Class 0, I and II protostars at the core of Serpens South's central filament. Radio contours start at the 4-sigma level.

We detect 18 radio sources in our field of view. Figure 2 shows a subset of 8 of these sources focused on the highly clustered central filament. It 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 (left). Shorter wavelengths around 3.6 μm tracing heated dust give more accurate spatial positions and detect high numbers of Class I and II candidates (right) but are blind to young and embedded protostars. The rest of our sources are background sources, similar to the lower-left source in Figure 2.

Our radio images confidently detect compact radio emission from new embedded Class 0 protostars and previously identified Class 0, I and II protostars, and show how the gas in Serpens South fragments into compact protostellar sources. This will benefit further studies that aim to correlate the radio properties of these protostars to other wavelengths, such as X-ray flux. This work also sheds light on the radio properties of protostars in a highly clustered environment. We have, for example, detected four embedded protostars within an angular separation of 30 arcseconds (0.06 pc), two of which are candidates for driving large scale outflows (Figure 3).

4. Discussion: Outflows and Lbol Correlations

Outflows:

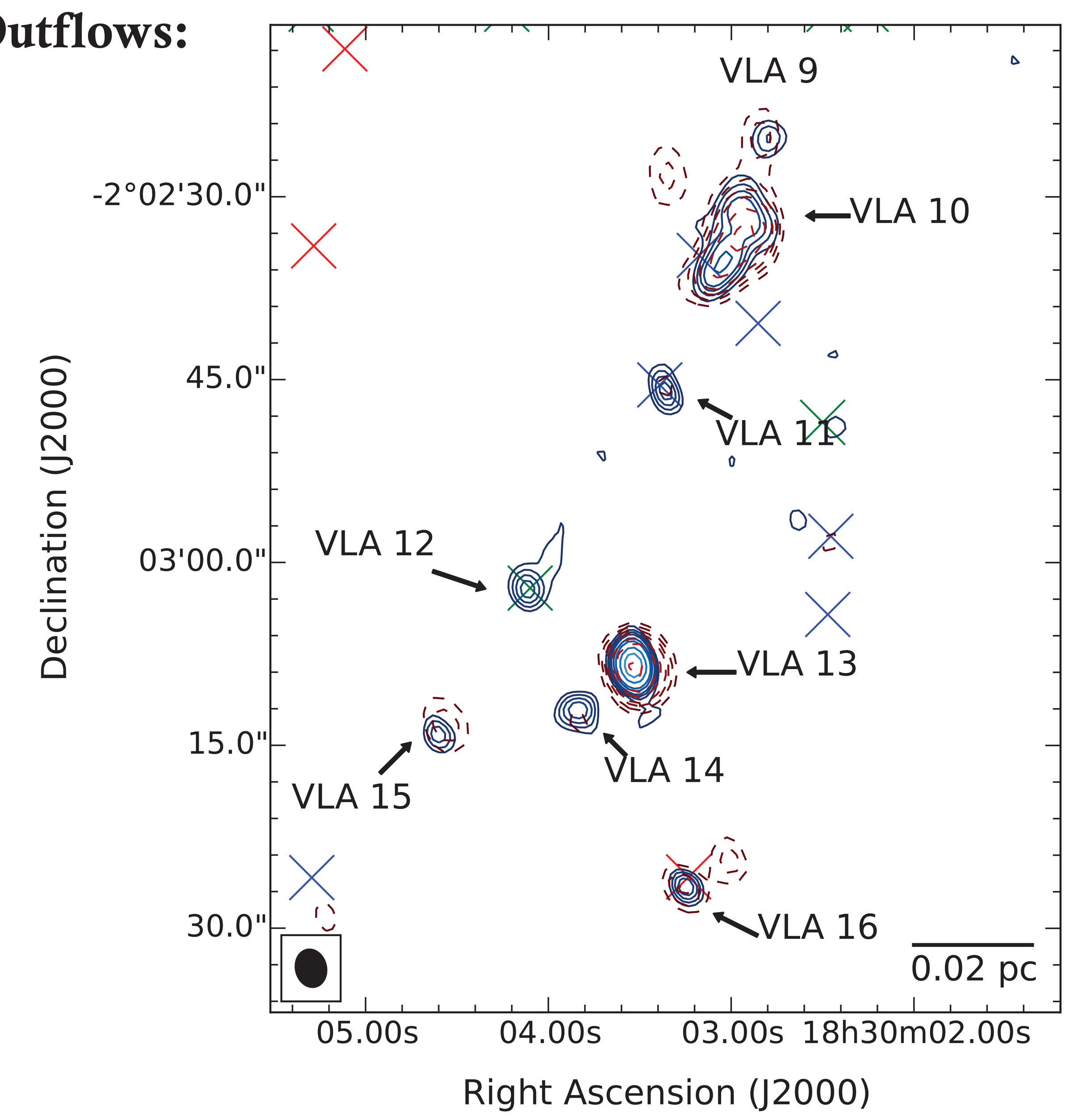

Figure 3: Radio contour images of sources 9 through 16. Blue solid contour and red dashed contour correspond to 4.1 and 6.3 cm images respectively. Blue and red crosses indicate Spitzer identified Class I and II protostars, respectively, while green crosses indicate millimeter emission peaks. Beam size represents 4.1 cm resolution.

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 infalling material[3]. Teixeira et al 2012 conducted an 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 corresponding to VLA 11 and 13, both of which exhibit elongation in the direction of Teixieira et al. 2012's quoted outflow direction. Both of these candidates are Class 0 protostars, which supports the notion that protostars can drive outflows even in their infancy.

Radio Luminosity vs. Bolometric Luminosity:

A correlation between radio luminosity and bolometric luminosity has been shown to exist at centimeter wavelengths[2,3,6]. Shirley et al. 2007 compiled a decade's worth of radio observations and presented an updated relationship L_{radio} vs. $L_{bolometric}$ at 3.6 cm and 6.0 cm (Figure 4). This relationship is thought to represent the positive correlation between outflow force and bolometric lumionosity in low and intermediate mass protostars.

Complete SEDs cannot be constructed due to source blending longward of 70 μm. Therefore, we use an infrared luminosity-to-bolometric luminosity relationship defined by Kryukova et al. 2012. For five protostellar sources, we find relative agreement within our errors, however, deviation could arise because these might not be low-mass protostars.

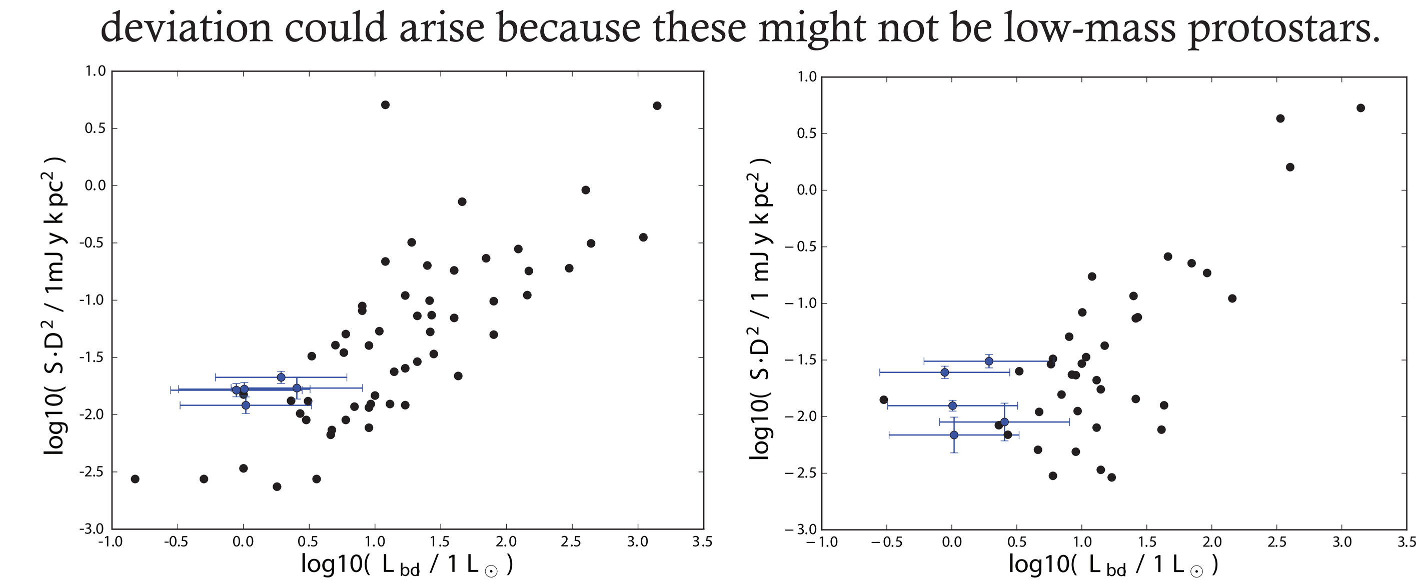

Figure 4 above: Relationship between protostellar radio luminosity and bolometric luminosity. Black represents Shirley et al. 2007 figure, while blue points represent protostars from this work. **Left:** 3.6 cm radio lumionsity. **Right:** 6.0 cm radio lumionsity.

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.
- With a multiwavelength data set, we compare our protostellar radio fluxes to the known radio 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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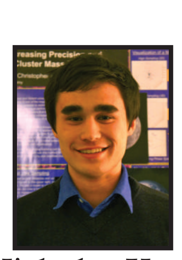

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