The Nature of VeLLOs

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Abstract

Very Low Luminosity Objects (VeLLOs) are young stellar sources that are defined by luminosities less than 0.1 $L_\odot$ while still embedded within dense molecular cloud cores. But, what exactly are they? Brown dwarfs or low-mass stars in formation? Systems exhibiting low accretion rates? Extremely young objects? We have completed an ALMA survey of 33 candidates in the nearby Serpens, Ophiuchus, and Lupus star-forming molecular clouds. Continuum emission at 1.3 mm, consistent with the presence of an inner envelope and/or disk, was detected toward 18 candidates, with at least 6 of these candidates exhibiting CO outflow emission, suggesting ongoing formation. We will present these observations and results, and discuss their implications concerning the nature of VeLLOs.

Introduction

The prototype VeLLO is L1014-IRS, with $L_{int} \leq 0.09\ L_\odot$, embedded within molecular cloud core L1014 at 200 pc (Young et al. 2004). It is associated with a weak compact CO outflow (Crapsi et al. 2005; Bourke et al. 2005). For a protostellar age of 10^5 years, the low luminosity suggests that the central source may have a mass of 20 – 25 $M_{Jupiter}$ (Huard et al. 2006). With about a dozen known VeLLOs to date (e.g., Kauffmann et al. 2005, 2011; Bourke et al. 2006; Lee et al. 2009; Dunham et al. 2010; Chen et al. 2012), the discovery rate of VeLLOs has been slow due to challenges in detecting their continuum and outflows with facilities prior to ALMA.

The currently known VeLLOs present a puzzle: accretion models that build low-mass stars predict accretion luminosities of ~1 $L_\odot$ during much of the formation. With VeLLOs possessing an envelope of material and exhibiting $L_{int} \leq 0.1\ L_\odot$, by definition, they must be either: (1) currently accreting material at much less than the standard rate, and/or (2) consisting of a central source with extremely low mass ($\ll 0.08\ M_\odot$). To further complicate the picture, VeLLOs show a range in CO outflow properties from weak and poorly organized to strong and well collimated (e.g., Dunham et al. 2006, 2010; Bourke et al. 2005).

Our Survey

Our goal is to increase the number of known VeLLOs in order to characterize the nature of these sources. We conducted an ALMA survey to detect dust continuum emission from inner envelopes and disks as well as to detect outflows from candidate VeLLOs. To be confirmed as a bona fide VeLLO, a source must exhibit continuum emission from an envelope and should show an outflow.

The sample of candidate VeLLOs was derived from the list of candidate embedded sources in Dunham et al. (2008), from which we further required that the candidate: (1) be observed in Spitzer IRAC and MIPS 24-μm; (2) have an internal luminosity $L_{int} \leq 0.1\ L_\odot$, estimated from MIPS fluxes; and (3) be observed toward a molecular cloud region of beam-averaged visual extinction $A_V > 5$ mag, based on extinction maps constructed with >1′ beams. These additional requirements were meant to provide a large sample of VeLLO candidates that could be quickly surveyed with ALMA.

In total, 33 candidates were surveyed for 1.3-mm continuum and CO J=2-1 line emission, with spectral channels providing a resolution of 0.159 km/s. The sample included 8, 11, and 14 candidates toward Serpens, Ophiuchus, and Lupus, respectively, each observed for 2.0 – 4.5 minutes, depending on distance, in order to reach a dust mass sensitivity of $\lesssim 10^{-3}\ M_\odot$. We achieved RMS noise values of 0.06 – 0.2 mJy/beam. The data were processed by the ALMA pipeline; then, the ALMA Data Mining Toolkit[3] (ADMIT) was used to detect and characterize continuum sources and line emission.

Conclusions

Of the 33 candidates surveyed, 15 were not associated with 1.3 mm-continuum or CO J=2-1 emission. Both continuum and CO outflow emission were seen toward 6 candidates, which represent the most likely VeLLOs. The 12 remaining candidates with continuum emission not clearly associated with outflows (4 candidates with "complex" CO emission; 8 candidates with no extended CO emission) are less likely VeLLOs, although we cannot rule out large-scale outflows not probed by our survey.

The ALMA data must be further analyzed to determine which continuum sources are consistent with emission from an inner envelope.

References

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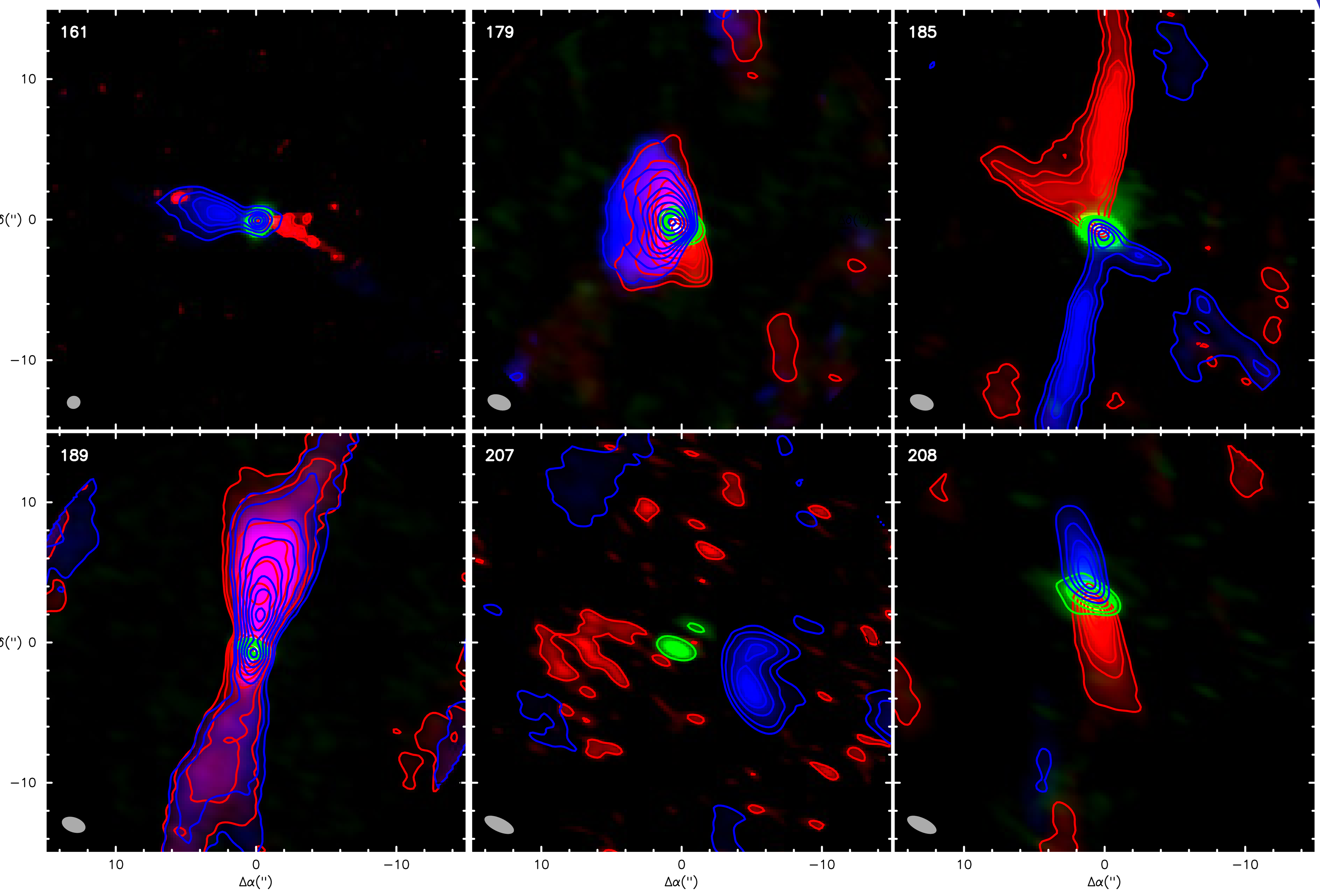
[3]ADMIT: Teuben et al. 2015, ADASS XXIV, 495, 305 (http://admit.astro.umd.edu)

Observational Results

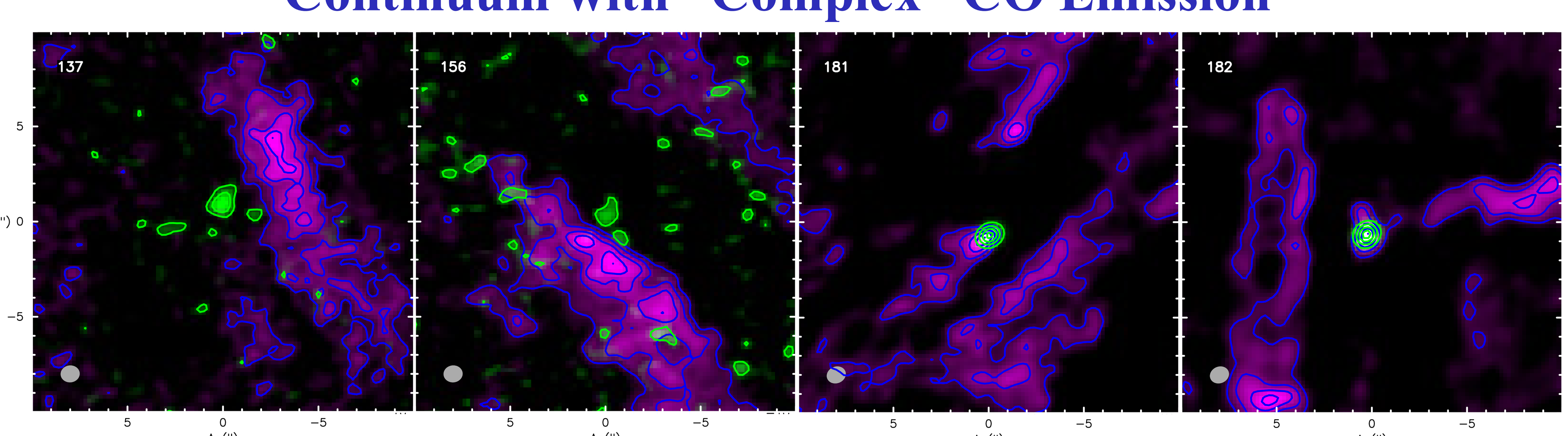
Based on the observations, the VeLLO candidates may be grouped into 4 categories: (1) those with continuum and CO detected indicative of an outflow; (2) those with continuum and "complex" CO detected with no apparent outflow morphology; (3) those with only continuum detected; and (4) those with no continuum or CO detected. The ALMA observations of the candidates in the first three groups are illustrated below.

Continuum with CO Outflows



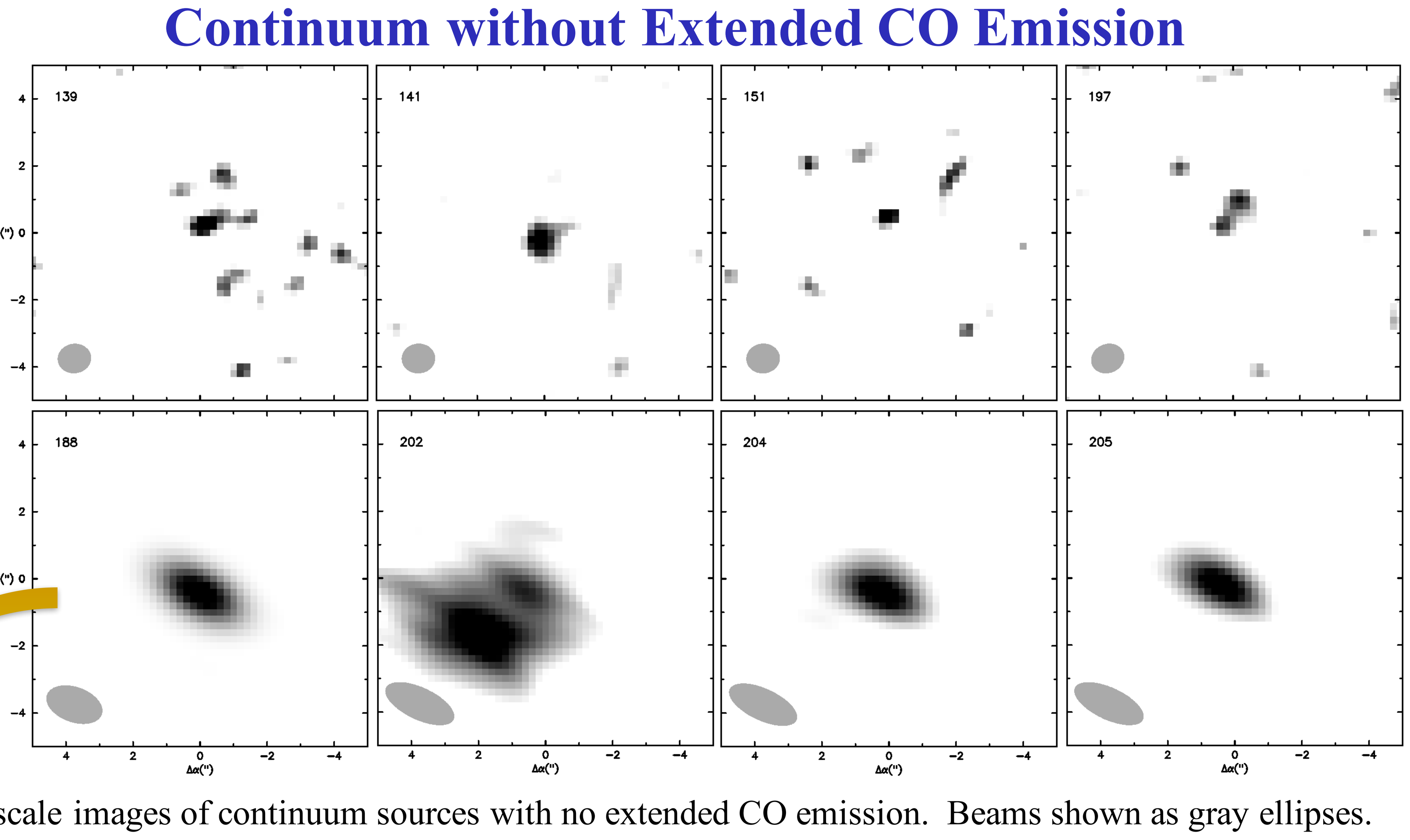
RGB images (G = continuum; R = integrated red-shifted CO; B = integrated blue-shifted CO), with contours showing outflow morphologies relative to continuum sources. Beams shown as gray ellipses.

Continuum with "Complex" CO Emission



RGB images (G = continuum; R = B = integrated CO), with contours overlaid showing continuum relative to CO emission. The CO emission for each of these sources could not be separated into red- and blue-shifted components to clearly identify an outflow. Beams shown as gray ellipses.

Continuum without Extended CO Emission



Grayscale images of continuum sources with no extended CO emission. Beams shown as gray ellipses.

Keplerian Disk

Source 188 is unique in our sample in that we have detected a gas disk in CO, in apparent Keplerian rotation, around the central source. The figures to the right show the rotational velocity of the gas: A) centroid velocity map; B) position-velocity diagram along the major axis of the disk with example Keplerian curves overlaid.