Cosmic Masers: Proper Motion toward the Next-Generation Large Projects
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Water Maser Zeeman Splitting in the Ionized Jet IRAS 19035+0641 A

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Abstract. A key ingredient in the earliest evolutionary phase of high-mass ($M > 8\,M_\odot$) star formation (HMSF) is the presence of a jet/outflow system. To study its role in HMSF, we have carried out high resolution ($0.1''$) VLA K-band (18−26.5 GHz) observations toward IRAS 19035+0641 A, identified as a high-mass protostellar jet candidate based on previous cm continuum data. Our observations resolve the continuum emission into an elongated structure in the NE-SW direction, confirming that the K-band continuum arises from an ionized jet. Furthermore, we detected several 22.2 GHz H_2O maser spots aligned in a direction consistent with the jet axis. Zeeman splitting was detected in the strongest maser spot. In this paper, we present our results and discuss the implications of our findings.

Keywords. Radio jets, Water masers, Massive stars, Magnetic fields

1. Introduction

The nature and role of ionized jets and magnetic fields in high-mass ($M > 8\,M_\odot$) star formation are still poorly understood, mainly due to lack of observations. The 22.2 GHz water (H_2O) maser transition arises in shocked gas regions and is therefore an excellent tool to study jet dynamics. This transition is also sensitive to Zeeman splitting, allowing us the ability to detect and study magnetic fields. We carried out a high resolution ($0.1''$) VLA 1.3 cm continuum survey toward 23 compact sources with a rising spectral index from Rosero et al. (2016), classified as jet candidates (Rodríguez et al. in prep.). Furthermore, our spectral set up allowed for simultaneous 22.2 GHz water maser observations. Here, we present and discuss our results for one of the target sources, IRAS 19035+0641 A.

2. Jet and Masers

We resolved the 1.3 cm continuum emission into an elongated structure shown in color in Figure 1 (left panel), as expected for an ionized jet. We identify a total of three continuum peaks aligned in a NE-SW direction, labeled as A1, A2, and A3 in the figure. The spectral index α (with $S_\nu \propto \nu^\alpha$) of the ionized gas is $\alpha = 0.9 \pm 0.1$. We also detected seven water maser spots well aligned with the jet, as shown in Figure 1 (right panel).

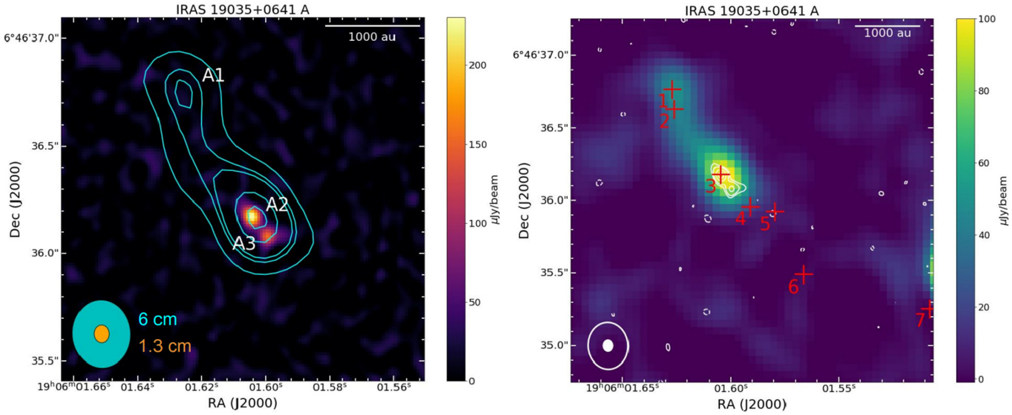

Figure 1. *Left*: 6 cm (contours, Rosero et al. 2016) and 1.3 cm continuum emission (color) toward IRAS 19035+0641 A. The three continuum peaks identified (i.e., A1, A2, A3) are labeled. *Right*: the 6 and 1.3 cm continuum emission is shown in color and contours (respectively), while the position of the water masers detected in the jet are marked with red + symbols and numbered.

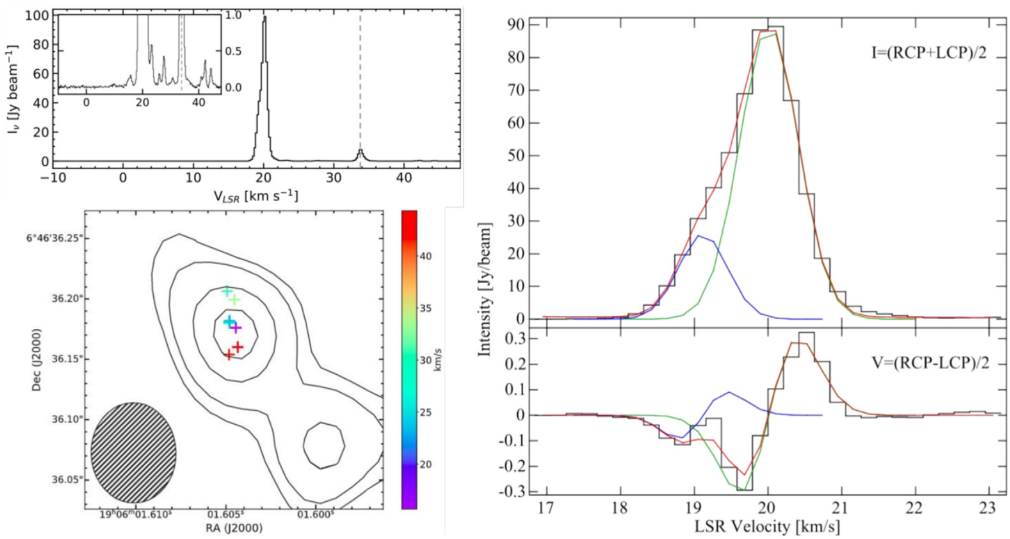

Figure 2. *Top-left*: Spectrum of maser #3, where the vertical dashed line marks the systemic velocity (33.8 km s^{-1}, Araya et al. 2005) and the inset shows a zoom-in to a 1 Jy beam^{-1} maximum. *Bottom-left*: Position obtained from 2-D Gaussian fits to each peak in the top spectrum, color coded by velocity, and overlaid on the 1.3 cm continuum contours. *Right*: Stokes I (top) and V (bottom) profile of the strongest maser #3 peak. The blue and green lines show the two Gaussian components fitted to the profile (top) and their derivatives scaled by their magnetic fields (bottom), while the red line is their sum.

Maser #3 is coincident with the continuum peak A2, is extremely bright (~ 100 Jy), and covers about 35 km s^{-1} in velocity with multiple peaks (Figure 2, top-left panel). We fit 2-D Gaussian to each peak in the maser #3 spectrum and found a NS velocity gradient (Figure 2, bottom-left panel). This gradient could be tracing expanding or rotating gas, although proper motion observations are needed to determine its nature.

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3. Zeeman Splitting

The Stokes I profile of the brightest maser #3 peak was fit with two Gaussian components, represented with a green and a blue line in Figure 2 (right panel). The Stokes V profile, which shows the S-shape typical of Zeeman splitting, is well represented by the derivatives of the two Gaussian components scaled by their respective line-of-sight magnetic fields $B_{\rm los}$, which are 135 and 156 mG. Following Crutcher (1999) and Sarma et al. (2002), we estimate a pre-shock gas density and magnetic field values of $\approx 10^7\,\rm cm^{-3}$ and $\approx 7\,\rm mG$, respectively. The magnetic energy density and the kinetic energy density in the post-shock gas were calculated as in Sarma et al. (2002), and we found that the magnetic energy is higher. This indicates the magnetic field is playing an important role in this post-shock region.

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