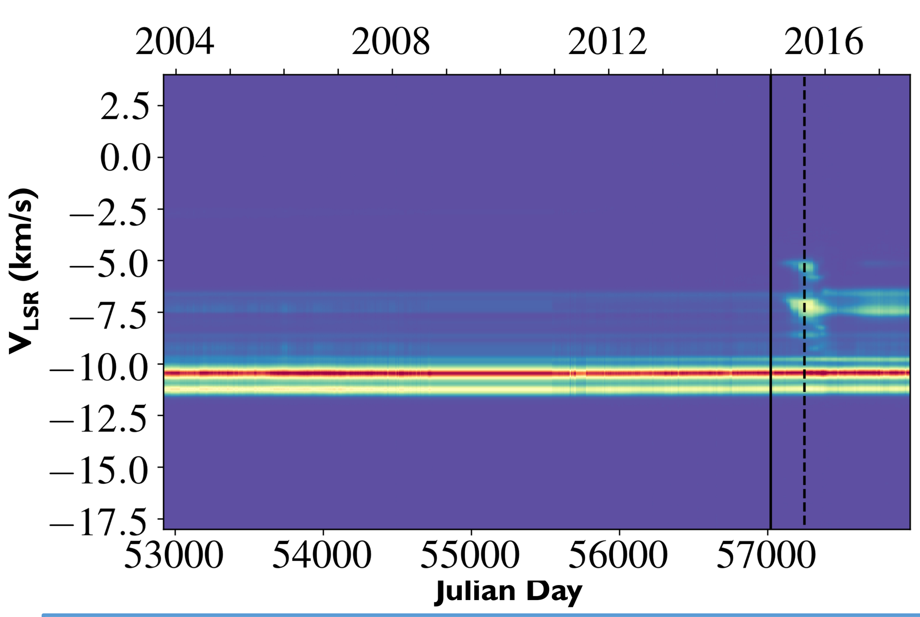
The Extraordinary Outburst in the Massive Protostellar System NGC6334I-MM1: the emergence of 6.7 GHz methanol masers

Todd R. Hunter[1], Crystal L. Brogan[1], Claudia J. Cyganowski[2], Gordon C. MacLeod[3], Rachel Friesen[1], James O. Chibueze[4], Claire J. Chandler[1], Tomoya Hirota[5], Remy Indebetouw[1,6], D. P. Smits[7]

([1]National Radio Astronomy Observatory, [2]Univ. of St. Andrews, [3]HartRAO, [4]SKA South Africa, [5]NAOJ, [6]Univ. of Virginia , [7]UNISA)

Abstract: Our 2015 and 2016 ALMA 1.3 to 0.87 mm observations (resolution ~ 200 au) of the massive protocluster NGC6334I revealed that an extraordinary outburst (luminosity increase of >70x) had occurred in the dominant millimeter dust core MM1 when compared with earlier SMA data from 2008 (Hunter et al. 2017, ApJL 837, L29). Here, we describe new results from our recent Karl G. Jansky Very Large Array (VLA) A-configuration observations of the 5 cm continuum and 6.7 GHz methanol masers in this region. These Class II masers had not previously been detected toward MM1 in any of the many interferometric observations recorded over the past 30 years that targeted the bright masers toward other members of the protocluster (MM2 and MM3 = NGC6334F). Strong masers now appear toward and adjacent to MM1 with the strongest spots located in a dust cavity about 1 arcsec (1300 au) north of the MM1B hypercompact HII region, along the same direction as a jet and the compact synchrotron source CM2. Toward CM2, we also detect new emission from the 6 GHz excited OH maser transitions. These data provide direct observational evidence of the effects of episodic accretion onto a deeply-embedded high mass protostar. **These data also demonstrate the need for higher sensitivity and higher angular resolution centimeter observations, enabled by ngVLA, to trace the changes in the accretion rate and jet properties during the formation of a massive protostar.**

HartRAO Single Dish Monitoring of the 6.7 GHz Class II Methanol Maser emission



Spectra from the VLA Image cubes from late 2016

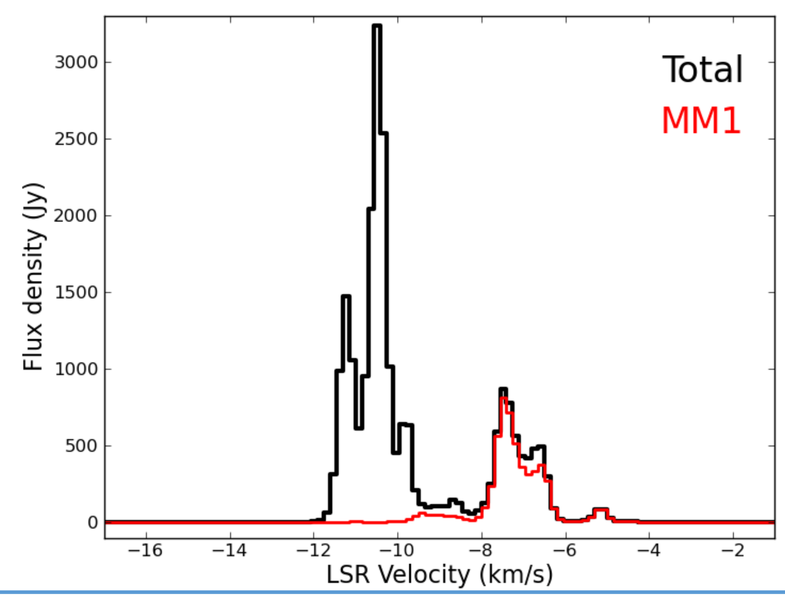


FIGURE 1: Left panel: The dynamic spectrum shows stable emission for the 11 years prior to the outburst in January 2015 (MacLeod et al. 2018, MNRAS, submitted). The maser emission near the LSR velocity of the hot core molecular gas in MM1 (-7 km/s) has persisted in outburst for 2 years, consistent with higher IR pumping radiation. **Right panel:** The VLA spectra show that the bursting emission comes almost exclusively from around MM1

Emergence of 6.7 GHz Methanol Masers surrounding the Massive Protostar MM1

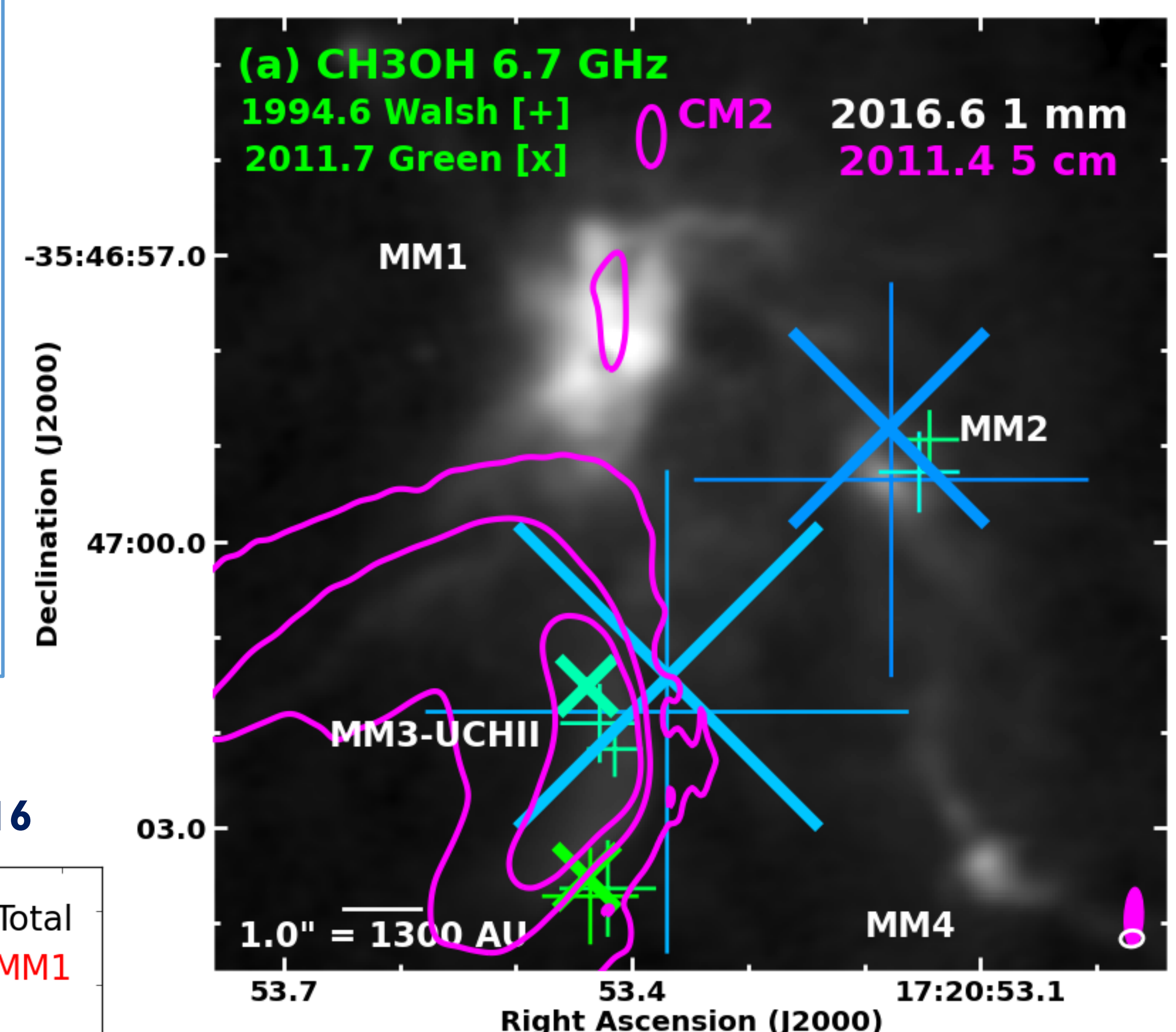


FIGURE 2: Prior to the millimeter continuum outburst, none of the interferometric observations of the 6.7 GHz methanol line had ever shown masers in the vicinity of MM1, (size of the symbols are proportional to flux density).

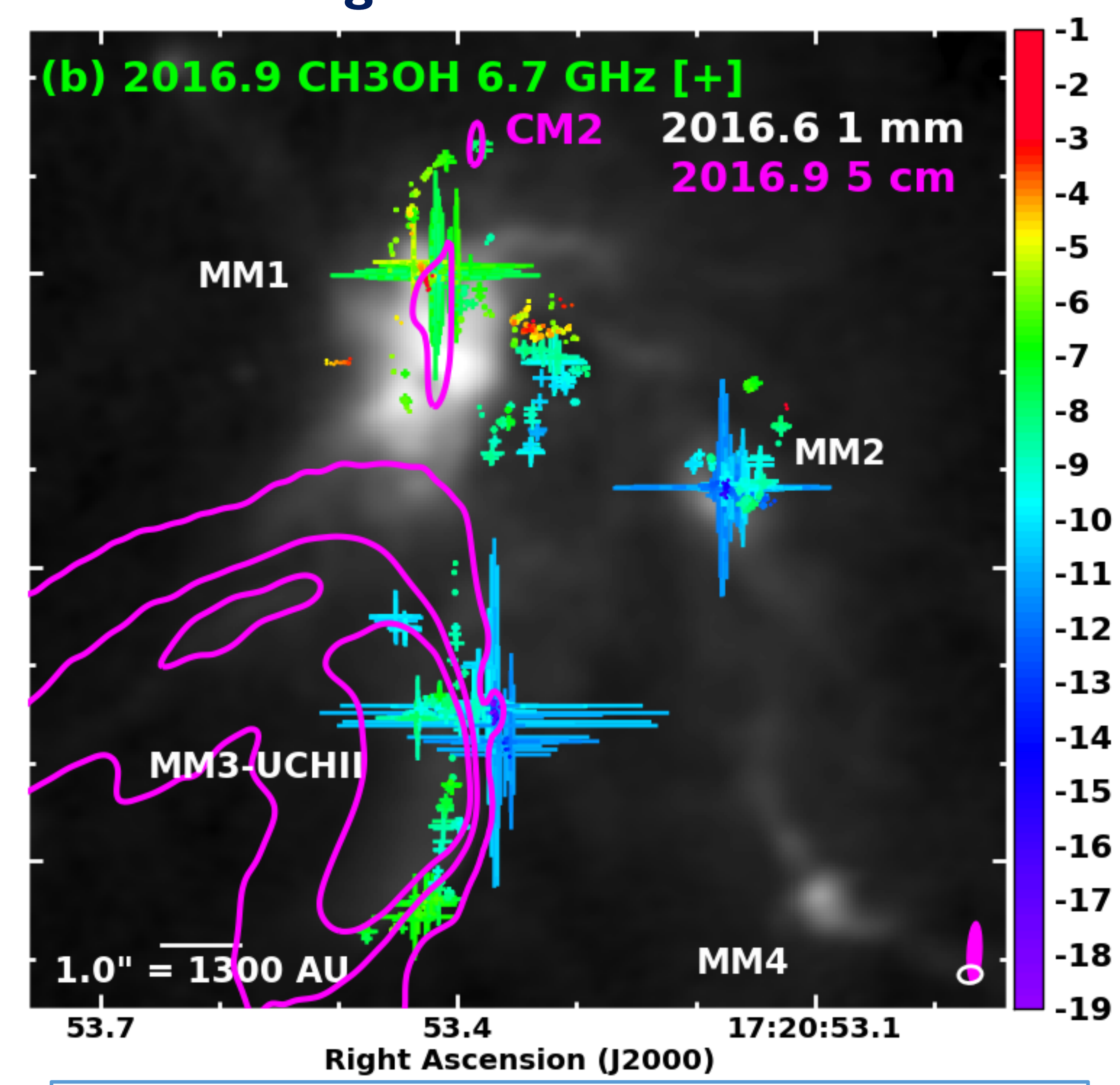
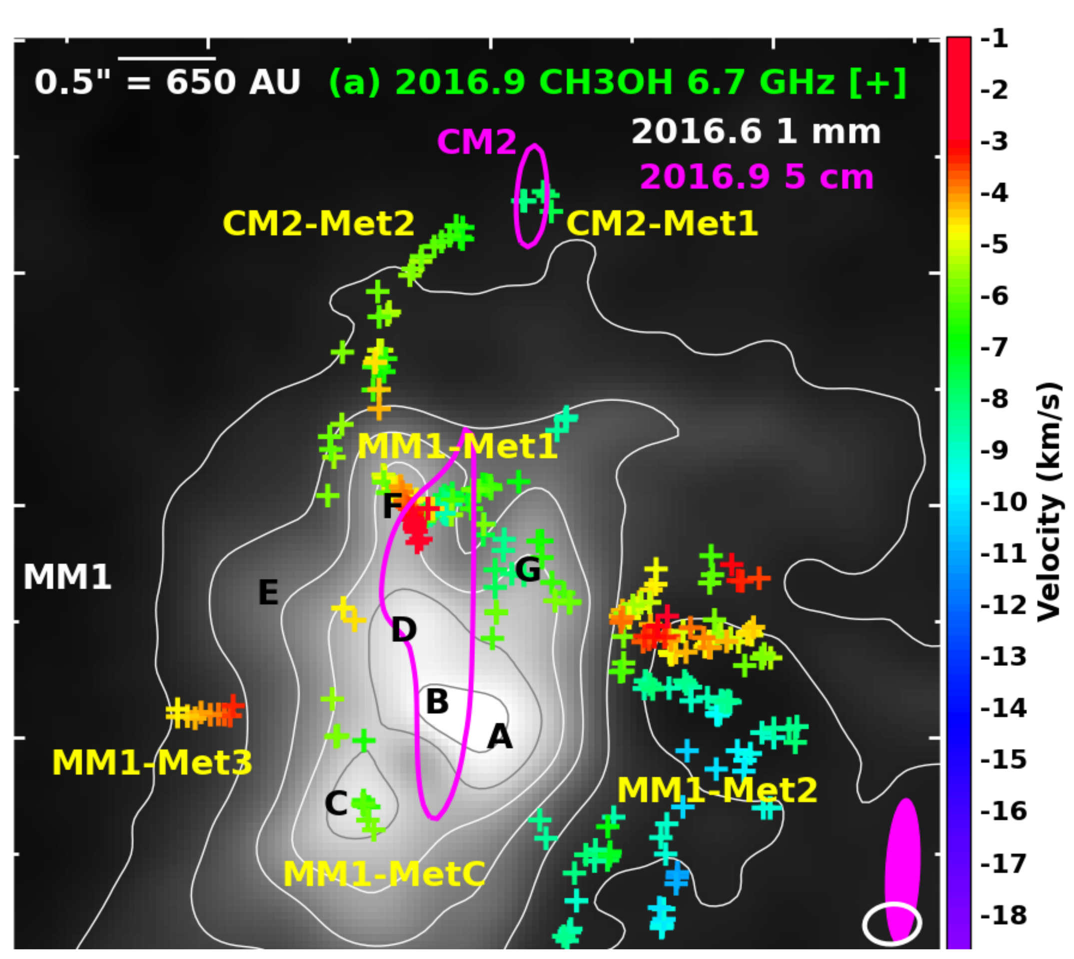


FIGURE 3: After the millimeter outburst (beginning in 2015), strong methanol masers now appear toward and surrounding MM1 and CM2, demonstrating the magnitude of the effect of the elevated protostellar accretion rate on the surrounding gas.

Detailed View of New 6.7 GHz Masers in the Vicinity of MM1

FIGURE 4:

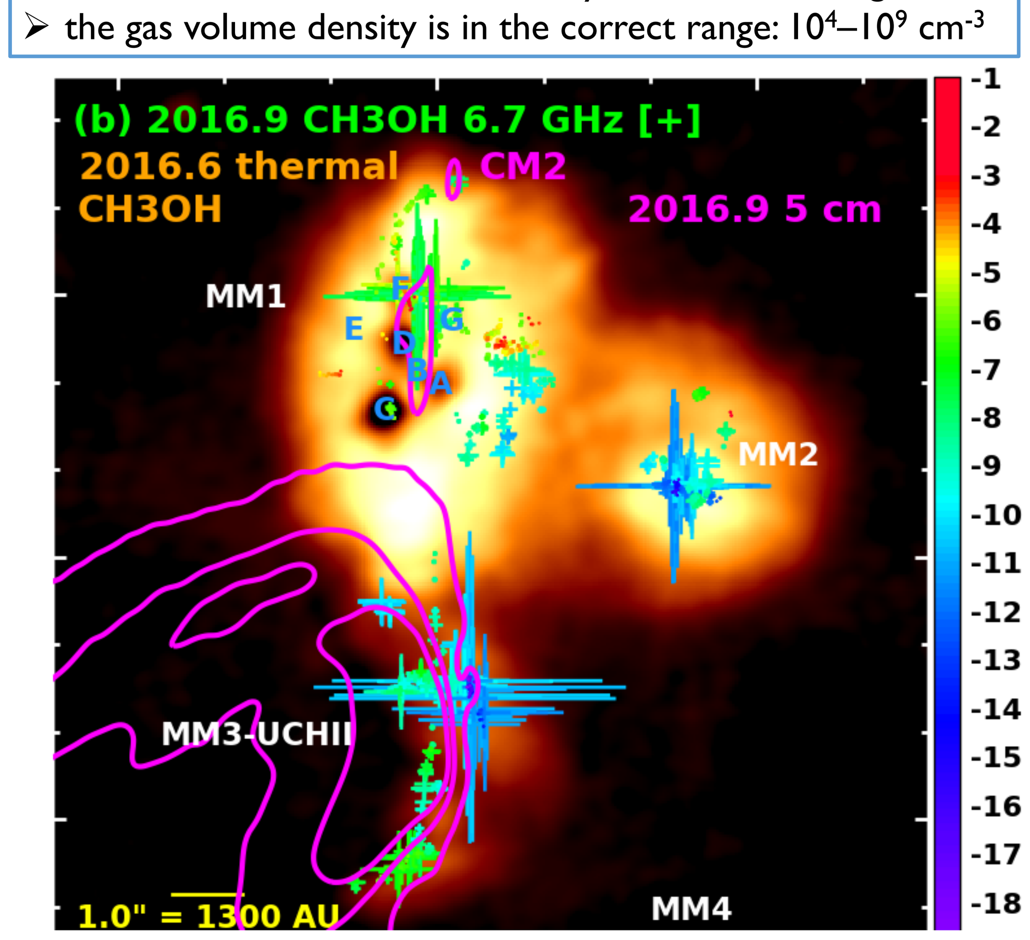
- The new masers do **not** appear toward the strongest millimeter continuum emission
  - Gas densities are likely too high (>10^9 cm-3) to support maser pump (Cragg et al. 2005).
- Instead, masers trace the surface of dust cavities north and west of the powering source (MM1B).
  - An arc of maser spots extends up to the non-thermal continuum source CM2, likely tracing a shock in the jet from MM1B.
- **Conclusion:** Photon propagation pathways allow the infrared radiation to escape from the vicinity of the central protostar and excite maser emission on the surface of gas clumps surrounding massive protostars.



Comparison of maser locations with thermal methanol emission from ALMA

FIGURE 5: This 279.35 GHz line of thermal methanol with E_{upper}=177K demonstrates that the 6.7 GHz methanol masers occur where:

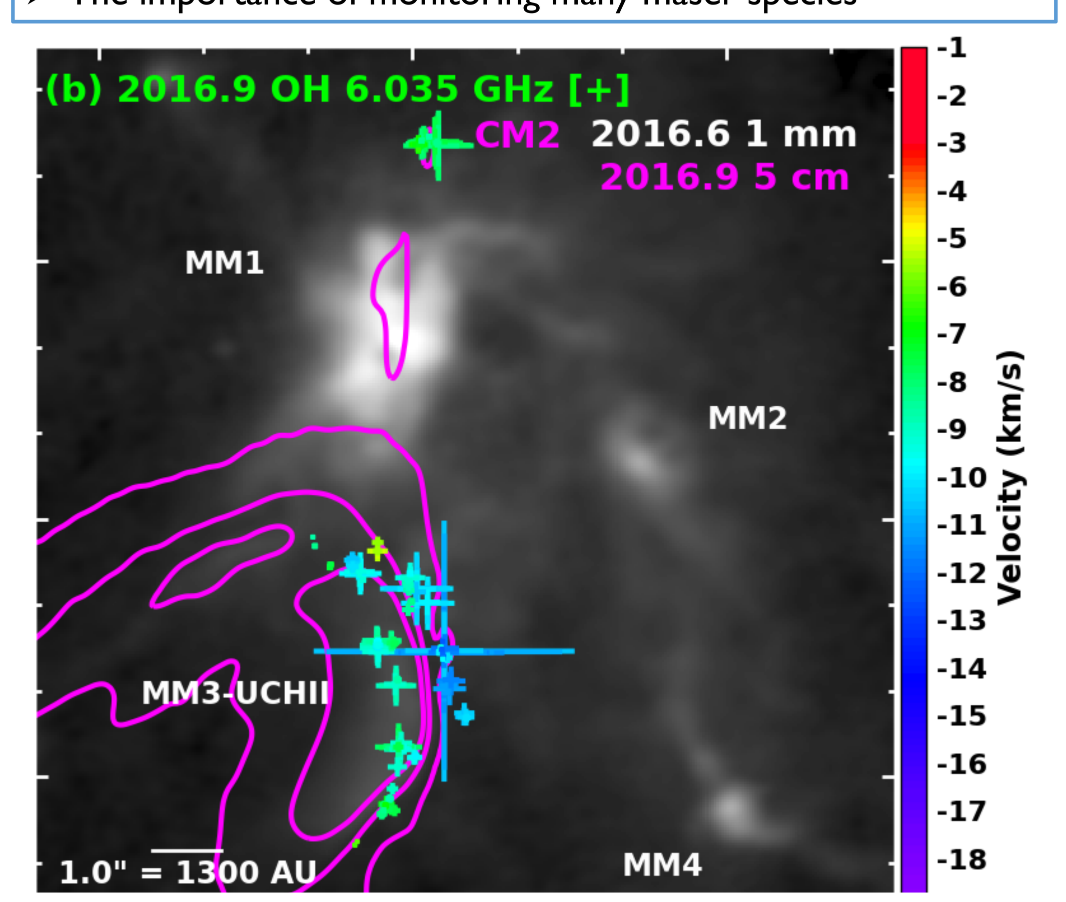
- the abundance and column density of methanol is high
- the gas volume density is in the correct range: 10^4–10^9 cm^{-3}



New maser emission from excited OH transitions (6.030, 6.035 GHz)

FIGURE 6: The appearance of new maser emission in CM2 in the excited OH transitions (which require >10^7 cm^{-3}) reveal:

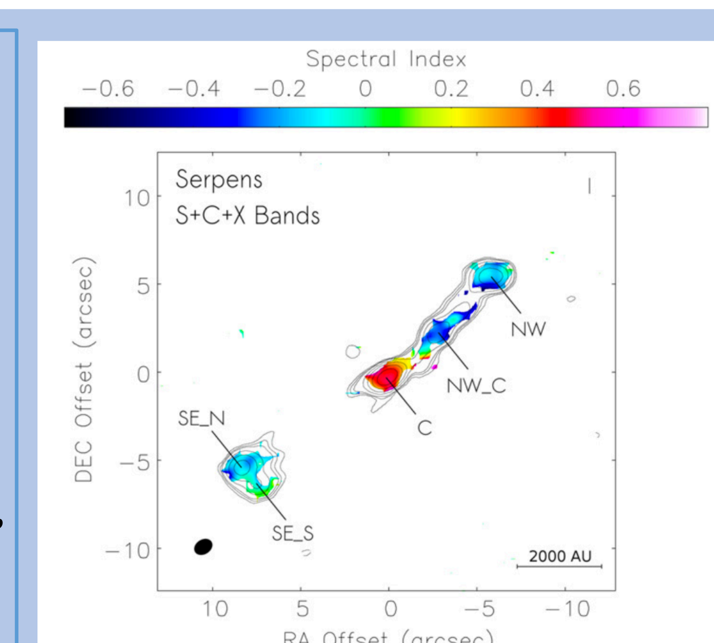
- Locations of interaction between the jet and dense gas
- Magnetic field strengths up to 3.7 mG (via Zeeman splitting)
- The importance of monitoring many maser species

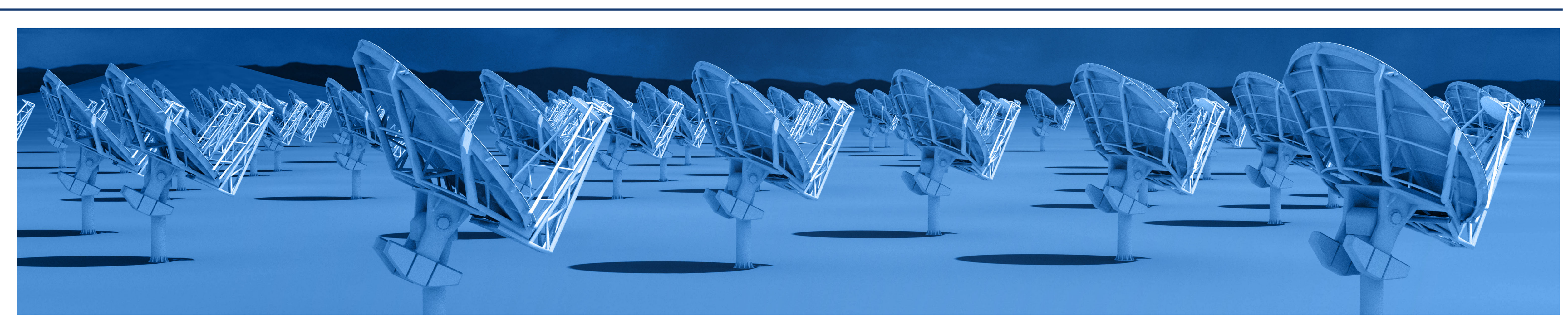


Major Advances Enabled by the ngVLA for Studies of Massive Protostars:

- **Continuum Sensitivity and Resolution:** with its increase in effective collecting area, the ngVLA will achieve 5x higher continuum sensitivity at frequencies where the emission from ionized jets is strongest (4-10 GHz). The current VLA resolution in this band (~0.3 arcsec = 400 au at 1.3kpc) cannot resolve these jets from high mass protostars. The ngVLA SW214 configuration (baselines up to 600 km) will achieve <0.03 arcsec resolution (40 au at 1.3 kpc) which will probe the launch point, emission mechanism, and structure of the jets (see Fig. 7).
- **Broad frequency coverage enabling simultaneous monitoring of many maser species:** with its broader frequency bands, the ngVLA will make it easier to periodically monitor all maser transitions in the cm band after an accretion outburst from a massive protostar. Important lines include: methanol (6.7, 9.9, 12.2, 19.9, 23.1, 36.2, 37.77, 44.1 GHz), OH (1.6, 4.66, 4.77, 6.03, 6.035 GHz), H2CO (4.8 GHz) and water (22.2 GHz).

FIGURE 7: Multi-frequency synthesis VLA B-configuration image of an ionized jet from an intermediate mass protostar in Serpens (412pc) by Rodriguez-Kamenetzky et al. 2016, ApJ 818, 27. The ngVLA SW214 configuration will enable images at an even finer scale (150au) at distances out to 5 kpc, encompassing many more regions of massive star formation.





The National Radio Astronomy Observatory is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.