***Understanding Massive Star Formation through Maser Imaging***

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**Change Record**

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| 1.01 | 03/18/2017 | Hunter | All | First draft. |
| 1.02 | 03/21/2017 | Hunter | All | Added mention of extragalactic star formation from Ecosystems white paper |
| 1.03 | 03/22/2017 | Hunter | 2D, 3, 4 | Added synergies, performance requirements and references |

*ngVLA Science Use Case # XX*

**Understanding Massive Star Formation through Maser Imaging**

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**I. Science Goal(s)**

Imaging the bright maser emission produced by several molecular species at centimeter wavelengths is an essential tool for understanding the process of massive star formation by probing the kinematics of the molecular gas at high angular resolution. Unimpeded by high dust optical depths, their high brightness temperatures offer a way to resolve accretion and outflow motions down to scales of ~10 au in Galactic massive star-forming regions, and at sub-pc scales in nearby galaxies.

**II. Scientific Rationale**

**(A) Scientific Importance**

The process of star formation leads to the concentration of molecular gas to high densities in molecular cloud cores. The potential energy released by gravitational collapse and accretion onto the central protostars heats and excites the surrounding material through infrared radiation and high velocity bipolar outflows. Both of these feedback mechanisms naturally produce population inversions between specific pairs of energy levels in several abundant molecules, including H2O, CH3OH, OH, NH3, SiO, and H2CO. The resulting non-thermal maser emission in the corresponding spectral transition provides a beacon whose brightness temperature far exceeds the more common thermal emission lines. Consequently, maser lines at centimeter wavelengths have provided a powerful probe of star formation through single-dish surveys and interferometric imaging. In general, they trace hot, dense gas, revealing the kinematics of star-forming material close to the central protostars, including accretion disks and their associated jets, as well as shocks in the outflow lobes where the jets impact ambient gas. Masers are generally more prevalent in the regions surrounding massive protostars, due to their higher luminosities and more energetic outflows. With the advent of ALMA, imaging thermal lines at high resolution has become easier, however not with enough brightness sensitivity at the resolution required to trace the accretion structures surrounding massive protostars. Moreover, the combination of line confusion and high optical depth of dust will block the most interesting details from ALMA's view. In contrast, the centimeter maser transitions propagate unobscured from the innermost regions, providing a strong signal for self-calibration, thus enabling high dynamic range imaging on long baselines. Unfortunately, the angular resolution of the VLA is insufficient to resolve the details of accreting gas, particularly in the 4-6 GHz band where the beamsize is limited to ~0.3 arcsec. In the nearest examples of massive star formation (d ~ 1 kpc), this corresponds to 300 au (e.g. Brogan et al. 2016), while in the more typical regions, such as in the 3 Kpc arm (d ~ 5kpc), it corresponds to 1500 au, which is often more than the separation of protostars in the center of protoclusters. Thus, an order of magnitude improvement in angular resolution (~300 km baselines) is needed to resolve the structure of individual disks (10-100 au) in a large sample of massive protostars. Such a resolution would also enable three dimensional measurements of gas velocity via multi-epoch proper motions. In one spectacular nearby case (Orion KL), movies of the vibrationally-excited SiO 43 GHz transition have revealed a complicated structure of disk rotation and outflow (Matthews et al. 2010). Studying additional objects at greater distance in a comprehensive list of maser lines will be an important task for ngVLA. With 300 km baselines, it will also be possible to trace molecular gas structures down to 0.2-pc scales in the star-forming clouds in nearby extragalactic nuclei (e.g. Maffei2 / IC342 / M82) in the bright water and Class I methanol maser lines.

**(B) Measurements Required**

The Class II CH3OH maser lines, primarily at 6.7, 12.2 and 19.9 GHz, trace hot molecular gas very close to the youngest massive protostars because they provide the required infrared pumping. Quasi-periodic flares in the 6.7 GHz line (120-500 days) have been observed in about a dozen objects (e.g. Goedhart et al. 2014). In one case, the 4.83 GHz H2CO maser shows correlated flaring (Araya et al. 2010), suggesting that maser flares are caused by a variable accretion rate onto the central protostar. The Class II CH3OH maser lines, along with several lines of excited OH (at 4.66, 4.76, 6.030, and 6.035 GHz), are also seen to trace the ionization front of ultracompact HII regions, which are powered by somewhat more evolved protostars. The strong water maser line at 22 GHz also traces gas close to massive and intermediate mass protostars. In some cases it clearly arises from gas in the first few hundred au of the jet, which can exhibit very broad linewidths. In contrast, the Class I CH3OH maser lines at 25, 36, 37, 44, and 95 GHz and the NH3 (3,3) and (6,6) lines at 23.87 and 25.06 GHz typically arise from collisionally-excited gas located much further from the protostar where the bipolar outflow lobes impact ambient gas, and are often coincident with 4.5 micron emission (Cyganowski et al. 2009). The Class I CH3OH masers are particularly abundant in the Galactic center star-forming clouds, and with ngVLA sensitivity, could be used to probe such clouds in nearby galaxies (Maffei 2 / IC 342 / M82).

Many maser lines are significantly polarized, thus it is important to observe them with full Stokes products in order to obtain the highest fidelity imaging. Furthermore, recent full polarization images of various methanol maser lines (e.g. Momjian & Sarma 2017) and the 22 GHz water line (Goddi et al. 2017) have been used successfully to measure the magnetic field toward massive protostars via Zeeman splitting. These maser lines thus offer potential to understand the degree to which magnetic fields influence massive protostellar accretion.

**(C) Uniqueness to ngVLA Capabilities (e.g., frequency coverage, resolution, etc.)**

With its proposed frequency span, the ngVLA will uniquely provide access to all of the most important maser transitions from C-band through W-band. While the LBO also covers this span, it lacks the sensitivity at the critical baseline lengths of up to 300 km. The ngVLA will provide the required balance between resolution and brightness sensitivity. The ability to rapidly cover all of these maser lines in just a few tunings will allow much more rapid progress in understanding the aggregate information that they carry.

**(D) Longevity/Durability: with respect to existing and planned (>2025) facilities**

The science described here will share many synergies with other future facilities. Of course, ALMA will likely be the closest complementary facility as it can observe the dust emission and strong thermal lines at comparable angular resolutions. SKA will provide access to lower frequency masers, such as OH at 1665, 1667 and 1712 MHz, as well as covering the southern Galactic plane in the maser lines that will be accessible in its highest frequency bands. Toward many target regions, TMT/E-ELT imaging at mid-infrared wavelengths will be quite informative as it can potentially deliver 0.05-0.2 arcsec resolution at 7-28 microns. The short wavelengths will delineate outflows on larger scales, while the longer wavelengths (combined with ALMA observations) will enable measurements of the luminosity of the individual massive protostars.

**III. Science Requirements Tables**

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| **(A) ‘TARGETS’ OF OBSERVATIONS** | | |
| Type of observation  (what defines a ‘target’) | X | Individual pointings per object |
| X | Individual fields-of-view with multiple objects |
|  | Mosaics of multiple fields of view |
|  | Non-imaging pointings |
| Number of targets | 100 | |
| Position range of targets (RA/Dec.) | RA: 17-22 Dec: -35 to +60 | |
| Field of view (arcmin2) | 1 | |
| Rapidly changing sky position?  (e.g., comet, planet) |  | YES [details: ] |
| X | NO |
| Time Critical? |  | YES [details: ] |
| X | NO |
| Required rms (μJy/bm) [per km/s for lines] | 5 mJy/beam at 0.1 km/sec | |
| Peak brightness (μJy/bm) | 100 Jy/beam | |
| Expected polarized flux density  (expressed as % of total) | 1-10 | |

**(A) ‘Targets’ of Observations Discussion**

In some cases, the peak intensity in some masers can be higher than 100 Jy/beam (a few kJy is seen during flares), and so these channels of the spectrum will undoubtedly be dynamic-range limited.

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| **(B) OBSERVATIONAL SETUP** | | | | | |
|  | Tuning 1 | | Tuning 2 | Tuning 3 | Tuning 4 |
| Central Sky Frequency(ies) (GHz) | 4.66, 4.77, 4.83, 6.030, 6.035, 6.67, 9.9, 12.2 | | 19.9, 22.235, 23.87, 25.06,  24.93, 24.96, 25.29, 25.88 | 36.2, 37.7, 42.8, 43.1, 43.4, 44.1 | 84.5, 85.6, 86.2, 86.8, 95.1, 96, 104.3 |
| Instantaneous Bandwidth for each Sky Frequency (GHz/pol; max 40GHz) | 8 GHz for full continuum; 4MHz for each line | | 8 GHz for full continuum; 8MHz for each line | 12 GHz for full continuum; 16MHz for each line | 25 GHz for full continuum; 16MHz for each line |
| Spectral resolution(s) [km/s or kHz] | * 1. km/s | | 0.1 km/s | 0.1 km/s | 0.1 km/s |
| Temporal resolution (in seconds) |  | YES [details: ] | | | |
| X | NO [*set by time/bandwidth smearing considerations*] | | | |
| Subarrays | N | | | | |
| VLBI |  | YES [details, including phased field of view: ] | | | |
| X | NO | | | |

**(B) Observational Setup Discussion**

The spectral resolution of 0.1 km/s is needed only for the narrow bandwidth windows centered on each line. The bulk of the continuum band can be observed with coarser channels, simply narrow enough to avoid smearing effects.

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| **(C) POLARIZATION DATA PRODUCTS REQUIRED** | |
| Y | Stokes I |
| Y | Stokes Q |
| Y | Stokes U |
| Y | Stokes V |

**(C) Polarization Product Discussion**

For maximum flexibility, it should be possible to revert to dual-polarization observations in order to double the highest spectral resolution (number of channels) available for certain experiments.

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| **(D) IMAGING CONSIDERATIONS (Continuum & Line, Including VLBI Observations)** | | |
| Required angular resolution (mas)  (single value or range) | 30 at 6.7 GHz; 5 at 40-100 GHz | |
| Largest angular scale required (arcsec) | 1 | |
| Mapped image size (arcmin2) | 1 | |
| Required pixel resolution (mas) | 6 at 6.7 GHz; 1 at 100 GHz | |
| Number of output/image channels | 1024 per line, 8192 total + continuum | |
| Output bandwidth (minimum and maximum frequency - GHz) [Continuum] | 4.5-12.5 GHz; 19-27 GHz; 27-49 GHz; 80-105 GHz | |
| Channel width (km/s or kHz) [Spectral line] | 0.1 km/s | |
| Required rms (μJy/bm) [per channel for spectral line] (if polarization products required define for each) | 5 mJy/bm | |
| Dynamic range within image  (if polarization products required define for each) | 20000 | |
| Polarization accuracy (%) | 0.1 | |
| Required polarization angle accuracy (deg) | 6 | |
| Zero spacing/total power required? | N | |
| Required flux density scale calibration accuracy |  | 1-3% |
|  | 5% |
| X | 10% |
|  | 20-50% |
|  | n/a |

**(D) Imaging Considerations Discussion**

The mapped image size is only a mean value. Some targets may require several arcmin to properly cover all of the expected protostars in that region.

**(E) Other Functional Requirements**

While not strictly necessary, simultaneous observations in multiple bands would reduce the time required on the telescope for this science case.

**(F) Other Performance Requirements**

**IV. Appendix: References**

Araya et al. 2010, ApJ, 717, 133

Brogan et al. 2016, ApJ, 832, 187

Cyganowski et al. 2009, ApJ, 702, 1615

Goddi et al. 2017, A&A, 597, 43

Goedhart et al. 2014, MNRAS, 437, 1808

Matthews et al. 2010, ApJ, 708, 80

Momjian & Sarma 2017, ApJ, 834, 168