Polarization science in star and planet formation with the ngVLA

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ngVLA: motivated and complemented by ALMA

As an instrument of unprecedented resolution and sensitivity, ALMA is now providing significant new information about polarized emission from star and planet-forming objects. These have revealed that polarized emission can be dominated by self-scattering, radiative torques as well as magnetic field geometries. ALMA data also make a strong case for the need for polarized emission measures at longer wavelengths, but comparable sensitivities and resolution. In this science field, much of the key polarization signatures are carried by dust and molecular gas, so a facility operating up to 115 GHz is essential; this facility is the ngVLA.

- ngVLA will be able to probe self-scattering signatures from dust grains of larger size than ALMA (> 1 mm), critical for understanding grain growth in disk midplanes to pebble sizes. The self-scattering profile is also sensitive to disk shape.
- ngVLA will probe regions of protoplanetary disks and cores that are optically thick to ALMA, providing an observing window into the formation regime of terrestrial planets.
- ngVLA will allow us to probe fields in hot and cold cores as well as magnetic fields in high mass star forming objects in distant OB associations.
- ngVLA and ALMA data together will allow us to differentiate grain alignment signatures from scattering signatures, even in regimes optically thick to ALMA. This would allow us to characterize different dust grain populations.

Spectral line polarization

Polarization of spectral lines can result from Zeeman splitting or the Goldreich-Kylafis effect because molecular and atomic lines are sensitive to magnetic fields which cause their spectral lines to split into magnetic sublevels, dependent on the *strength* of the magnetic field. Polarization from thermal lines requires bright emission lines detected with a high signal-to-noise ratio at a high spectral resolution.

- Lines at frequencies between 1-50 GHz are will be the best for detection of Zeeman splitting in emission while detection in absorption against hot dust will be possible at higher frequencies.
- Linear polarization can also arise in molecular lines whenever an anisotropy in the radiation field yields a non-LTE population of magnetic sublevels (the Goldreich-Kylafis effect). This traces the field in the plane of the sky.
- Linear and circular polarization from maser emission of centimeter and millimeter lines of SiO, CH_3OH, H_2O, and OH would allow us to probe the dense environment around young stellar objects and the circumstellar material around evolved stars.

Synchrotron emission in jets and high mass SFRs

The ngVLA will allow us to investigate in unprecedented detail the role of magnetic fields in the formation of massive stars and clusters, from 20,000 AU (0.1 pc, or 300 at 6 kpc) to 100 AU scales. The ngVLA will be able to map the polarization in massive star-forming regions, where the influence of magnetic fields may differ from the more well studied local SFRs.

- Polarization related to synchrotron could be detected in the centimeter bands, while dust polarization could be observed in the millimeter (or ~1 cm) bands.
- High-mass star forming regions are very bright; therefore, despite their increased distance, the sensitivity and resolution of the ngVLA will allow us to perform statistically significant surveys of magnetic fields at high resolution (potentially even resolving high-mass disks) in high mass star forming regions, whereas to date such high-resolution surveys have only been possible in more nearby, low-mass star-forming regions.

Magnetic fields in protostellar cores and clouds

- Polarized emission from dust grains is well established in star-forming regions, and now in protoplanetary disks.
- Polarized emission has been well established as a probe of magnetic fields in star-forming objects, both on large scales (clouds) down to cores.

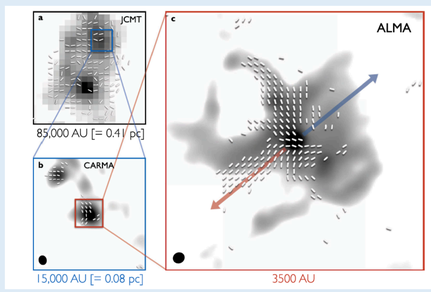


Figure 1. The power of increasing resolution is shown in the study of the protostellar core Ser-emb 8. Polarization data are shown from JCMT (Matthews+ 2009), CARMA (Hull+ 2014) and ALMA (Hull+ 2017). Colored arrows show the orientation of the outflow from the protostar. The ALMA data reveal that the field is consistent with being dominated by turbulence.

Dust Polarization in protoplanetary disks

- At high resolution in protoplanetary disks, ALMA observations have suggested self-scattering is instead a dominant mechanism and alignment by radiation anisotropies has also been suggested.

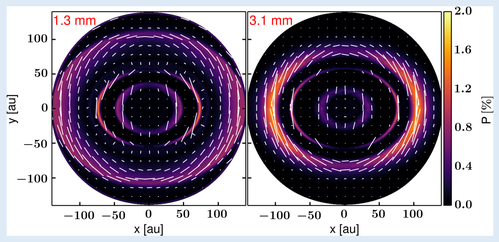
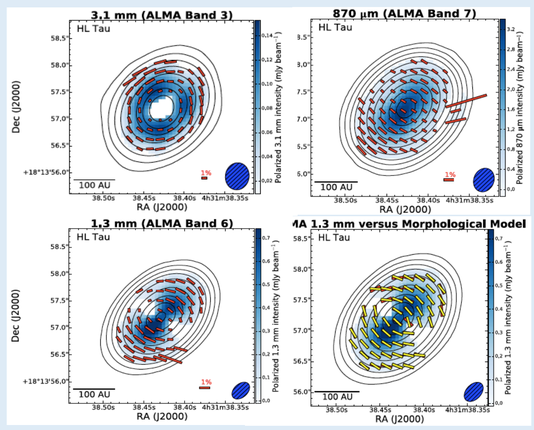


Figure 2. The polarization patterns by scattering are demonstrably different at ALMA Band 6 (left) and Band 3 (right). The simulations is for a disk at 1 Myr of dust evolution, viewed at an inclination of 40 degrees. (Pohl+ 2016)

Figure 3. Stephens+ (2017) show that the polarization patterns for HL Tau vary significantly with wavelength. They attribute the uniform pattern at 870 um to self-scattering. The 3.1 mm data of Kataoka+ (2017) are consistent with grain alignment due to anisotropy in the radiation field. The intermediate 1.3 mm wavelength shows a pattern consistent with an *equal combination* of the two mechanisms, as shown by an overlay of the line segments, model (yellow) versus data (red).



- Polarization of relatively small dust grains (<100 μm) s expected to arise because of dust grains aligned with magnetic fields, whereas large grains (>100 μm) should have polarization at radio wavelengths that is strongly frequency dependent.
- Dust settling appears to be an important and efficient mechanism in disks, so different sizes of dust grains may be significantly stratified disks. We can constrain the grain size from the scattering opacity, independent of the mean slope of the absorption opacity, measured from the spectral index of the dust. The power to probe larger grains is gained by the longer observing wavelengths of the ngVLA.

References

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