Disk Winds and the Evolution of Planet-Forming Disks

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Abstract. Disk winds are thought to play an important role in the evolution and dispersal of planet-forming disks. While high-resolution optical and infrared spectroscopy has identified several disk wind diagnostics, wind mass loss rates remain largely unconstrained mostly due to the lack of spatial resolution to measure the extent of the wind emitting region. Here, we show that the ngVLA will have the sensitivity and resolution to detect and spatially resolve the free-free emission from the fully or partially ionized component of disk winds. Hence, ngVLA observations will be critical to estimate mass loss rates and clarify the role of disk winds in the evolution and dispersal of disk mass.

1. Introduction

Disks of gas and dust around young (∼1–10 Myr) stars are active sites of planet formation. Hence, their evolution and dispersal directly impact which type of planetary systems can form. Accretion through the circumstellar disk is a ubiquitous phenomenon (see Hartmann et al. 2016 for a recent review) and thought to dominate disk evolution at early times (e.g., Alexander et al. 2014). However, the physical mechanism enabling accretion, and therefore global disk evolution, is as yet unclear (e.g., Turner et al. 2014).

The prevailing view for the past 40 years has been that accretion occurs because disks are viscous and transport angular momentum outward via correlated turbulent fluctuations. Magneto-rotational instability (MIR, Balbus & Hawley 1998) would produce the necessary turbulence. In this picture, viscous-dominated evolution lasts for the first few Myr of disk evolution until accretion drops below the mass loss rate from thermal disk winds driven by high-energy stellar photons, also known as photoevaporative winds. At that point photoevaporation limits the supply of gas to the inner (∼1 au) disk which drains onto the star on the local viscous timescale, of order 100,000 years (e.g., Gorti et al. 2016). Recently, simulations including non-ideal MHD effects have shown that most of the disk is not MRI active, hence not accreting onto the star (e.g., Bai & Stone 2013). Instead, these simulations develop vigorous magneto-thermal MHD winds that extract angular momentum from the disk surface and hence enable accretion (e.g., Gressel et al. 2015). In this scenario, wind mass loss rates are comparable
to mass accretion rates even at early times and disk dispersal can be rapid if the disk retains most of its magnetic flux during evolution (Bai 2016 but see also Zhu & Stone 2017). As the surface density evolution of a viscous disk is very different from that of a disk where accretion is driven by MHD winds, and surface density directly impacts planet formation, it is important to understand which physical process dominates. Detecting disk winds, spatially resolving them, and measuring wind mass loss rates is crucial to make progress in this field.

2. Disk wind diagnostics - the role of cm observations

Identifying disk winds and understanding their origin requires detecting gravitationally unbound/outflowing disk gas within a \(~30\) au radius from the star (e.g., Simon et al. 2017). Given the typical distance of star-forming regions (\(~140\) pc), this requirement translates into a spatial resolution better than \(~100\) mas. This is why most direct evidence for disk winds relies on spatially unresolved/high-resolution (\(\Delta v \sim 10\) km/s) optical and infrared spectroscopy of gaseous species probing the disk surface (see Ercolano & Pascucci 2017 for a recent review). Kinematic separation of different components in optical forbidden lines has demonstrated that MHD disk winds are present in the inner \(~0.5\) au for the majority of accreting stars while line ratios constrain the range of temperature-electron densities for the emitting gas (e.g., Simon et al. 2016). Infrared forbidden line profiles hinting to more radially extended disk winds that could be photoevaporative in nature have been also detected toward a dozen disks (e.g., Pascucci & Sterzik 2009, Sacco et al. 2012). The missing critical parameter for a reliable computation of wind mass loss rates is a measurement of the spatial extent of the wind emitting region.

As a fully or partially ionized disk surface emits free-free continuum radiation and H recombination lines, long mm and cm-wavelength observations can be also used to detect disk winds (Pascucci et al. 2012; Owen et al. 2013). Current radio facilities have identified candidate disk wind emission from the presence of emission in excess of the thermal dust emission and, when available, multi-wavelength cm observations have been used to exclude other possible sources of excess emission, such as gyro synchrotron non-thermal radiation and emission from very large cm-size grains or very small nanometer-size grains (e.g., Pascucci et al. 2014, Gálvan-Madrid et al. 2014). Even in these multi-wavelength studies, it remains difficult to properly separate free-free emission from a collimated fast (\(~100\) km/s) jet (e.g., Anglada et al. 1998) and from the ionized disk surface, which hampers measuring the disk ionization fraction and the wind mass loss rate. This is illustrated in Figure 1 which reports the 3.3 cm VLA image of GM Aur (Macías et al. 2016), a star surrounded by a disk with a dust cavity (e.g., Andrews et al. 2011; Oh et al. 2016). With a spatial resolution of 0.5”, \(~70\) au at the distance of Taurus-Auriga, an elongation perpendicular to the disk emission is barely detected. This elongation strongly suggests that a jet contributes to the excess cm emission even in disks that are thought to be substantially evolved. Higher spatial resolution and sensitivity are necessary to separate the jet and disk wind contributions.
Spatially resolving disk winds requires deep, multi-frequency radio continuum imaging at high angular resolution, and supplementary spectral imaging of H recombination lines. The continuum measurements target free-free emission from an ionized wind (and potentially jet). As dust thermal emission dominates at frequencies higher than 30 GHz, modest spectral coverage ($\Delta v/v \sim 0.8$) in the 5-30 GHz range is essential. For a photoevaporative wind heated and ionized solely by stellar X-rays and typical star/disk parameters the expected integrated flux density at 8 GHz is $\sim 3\mu$Jy (eq. 3 in Pascucci et al. 2012)\(^1\) and should arise within a $\sim 10$ au radius (Fig. 4 in Owen et al. 2013). Spatially resolving the emission in two beams and requiring a S/N of at least 5 means reaching an RMS noise level of 0.3$\mu$Jy/beam. Theoretical estimates for the free-free continuum (and H recombination line emission) from MHD winds have not yet been reported in the literature. However, observations tracing the jet and MHD wind of DG TauA hint at higher flux densities ($\sim 300$\,$\mu$Jy) distributed over the $\sim 0.1''$ beam of e-MERLIN (upper panel of Fig. 1 in Ainsworth et al. 2013).

In a fully or partially ionized optically thin region, such as a photoevaporative wind, the H line to free-free continuum ratios increase with frequency but so does the thermal dust emission. Unless the thermal continuum and H lines can be spatially separated, the best frequency to detect H lines is around 30 GHz (lower panel of Fig. 2 in Pascucci et al. 2012). At these frequencies, the integrated line flux densities from a photoevaporative wind are comparable to the free-free continuum emission ($\sim 3\mu$Jy) and a few percent of the total continuum (free-free + thermal dust), middle and lower panels of Fig. 2 in Pascucci et al. (2012). Line widths and blueshifts with respect to the stellar velocity depend on disk inclination but typical values are $\sim 10$ km/s (e.g.,

\(^1\)An EUV ionized layer would produce more free-free emission (eq. 2 in Pascucci et al. 2012) but observations suggest that the disk receives only a small fraction of the stellar EUV luminosity (Pascucci et al. 2014).
Alexander 2008; Ercolano & Owen 2010). Such line emission is probably too weak to detect even with the ngVLA. However, if the line emission from the jet has a similar flux density as the continuum it would detectable, and be particularly important for tracing the accretion and mass-loss in embedded protostars that are obscured at optical and infrared wavelengths. With 300$\mu$Jy distributed over 10 ngVLA beams obtaining a 5-sigma detection in a 5 km/s channel (to provide kinematic information) would take a few 10s of hours with the ngVLA; stacking multiple lines (all available in the 30 GHz band) would bring the time required down by a factor of the number of lines stacked.

4. Conclusions

In this contribution we have illustrated that the sensitivity and spatial resolution of the ngVLA can bring the study of disk winds to the next level. Although H recombination lines will remain challenging to detect, the free-free continuum emission of even a partially ionized disk surface can be separated by that of a jet and, for the first time, imaged.

The combination of collecting area and sensitivity at 30 GHz needed for this science is best matched by the ngVLA and will not be available with any other facility in the world. Although ALMA is expected to add Band-1, and perhaps array receivers, it will have the same sensitivity as the current VLA for point-source observations and the best resolution will be just over 100 mas. SKA is not currently expected to operate at frequencies as high as 30 GHz.

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\[1\] If H recombination lines would trace an MHD wind launched inside ~1 au line widths and blueshifts would be substantially larger (e.g., Romanova et al. 2009).
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