Gas Accretion within the Dust Cavity in AB Aur*

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Abstract

AB Aur is a Herbig Ae star hosting a well-known transitional disk. Because of its proximity and low inclination angle, it is an excellent object to study planet formation. Our goal is to investigate the chemistry and dynamics of the molecular gas component in the AB Aur disk, and its relation with the prominent horseshoe shape observed in continuum mm emission. We used the Northern Extended Millimeter Array interferometer to map with high angular resolution the J = 3–2 lines of HCO\(^+\) and HCN. By combining both, we can gain insight into the AB Aur disk structure. Chemical segregation is observed in the AB Aur disk: HCO\(^+\) shows intense emission toward the star position, at least one bright molecular bridge within the dust cavity, and ring-like emission at larger radii, while HCN is only detected in an annular ring that is coincident with the dust ring and presents an intense peak close to the dust trap. We used HCO\(^+\) to investigate the gas dynamics inside the cavity. The observed bright HCO\(^+\) bridge connects the compact central source with the outer dusty ring. This bridge can be interpreted as an accretion flow from the outer ring to the inner disk system proving gas accretion through the cavity.

Key words: circumstellar matter – planet–disk interactions – planets and satellites: formation – protoplanetary disks – stars: individual (AB Auriga) – stars: pre-main sequence

1. Introduction

AB Aur is a Herbig Ae star hosting a well-known transitional disk. Because of its proximity and low inclination angle, it is an excellent object to study planet formation. Our goal is to investigate the chemistry and dynamics of the molecular gas component in the AB Aur disk, and its relation with the prominent horseshoe shape observed in continuum mm emission. We used the Northern Extended Millimeter Array interferometer to map with high angular resolution the J = 3–2 lines of HCO\(^+\) and HCN. By combining both, we can gain insight into the AB Aur disk structure. Chemical segregation is observed in the AB Aur disk: HCO\(^+\) shows intense emission toward the star position, at least one bright molecular bridge within the dust cavity, and ring-like emission at larger radii, while HCN is only detected in an annular ring that is coincident with the dust ring and presents an intense peak close to the dust trap. We used HCO\(^+\) to investigate the gas dynamics inside the cavity. The observed bright HCO\(^+\) bridge connects the compact central source with the outer dusty ring. This bridge can be interpreted as an accretion flow from the outer ring to the inner disk system proving gas accretion through the cavity.

A handful of species were detected toward AB Aur using single-dish and interferometric observations (Fuente et al. 2010; Pacheco-Vázquez et al. 2015, 2016). Interferometric images of \(^{13}\)CO J = 2–1, C\(^{18}\)O J = 2–1, SO J = 5\(_{0}\)–4\(_{0}\), and H\(_2\)CO J = 3\(_{0}\)–2\(_{0}\) with an angular resolution of \(~1\arcsec 6 \times 1\arcsec 5\) testify to the complex gas chemistry occurring in the ring, which was found to be related with the gas dynamics. In particular, Pacheco-Vázquez et al. (2016) found a local minimum in the SO abundance toward the dust trap, which was interpreted as the gas vortex chemical footprint.

In this Letter we extend our chemical and dynamical study to smaller spatial scales by using higher resolution images of the HCO\(^+\) J = 3–2 and HCN J = 3–2 lines, which provide new insights into the evolution of the gas in this protoplanetary disk.

2. Observations and Data Reduction

We present high spatial resolution \(~0\arcsec 4 (~60 au at the distance of AB Aur) observations of the HCO\(^+\) J = 3–2 and HCN J = 3–2 lines in the AB Aur disk. The observations were carried out with the NOEMA interferometer in their A and C configurations. The observations in C configuration were...
Integrated intensity map of HCO$^+$ using uniform weight. Contour levels are 5σ to 40σ in steps of 4σ. (b) Integrated intensity map of HCN using natural weight. Contour levels are 5σ to 20σ in steps of 1σ. (c) Map of HCO$^+$ over HCN, using only channels with S/N > 5. Contour levels are 2σ to 24σ in steps of 4σ. (d) Integrated intensity map of HCO$^+$ with continuum intensity map at 1.12 mm overlaid as white contours. Continuum contour levels are 15σ to 40σ in steps of 10σ. (e) HCN integrated intensity map with HCO$^+$ overlaid as black contours (natural weights). HCO$^+$ contour levels are 20σ to 40σ in steps of 1σ. The 5σ level is also shown. Interesting positions in the maps are labeled in white. Integrated line intensity maps were built by integrating velocity channels between ±2 and ±10 km s$^{-1}$. Beam sizes are shown in the bottom-left corner of each plot.

Figure 1. (a) Integrated intensity map of HCO$^+$ using uniform weight. Contour levels are 5σ to 40σ in steps of 4σ. (b) Integrated intensity map of HCN using natural weight. Contour levels are 5σ to 20σ in steps of 1σ. (c) Map of HCO$^+$ over HCN, using only channels with S/N > 5. Contour levels are 2σ to 24σ in steps of 4σ. (d) Integrated intensity map of HCO$^+$ with continuum intensity map at 1.12 mm overlaid as white contours. Continuum contour levels are 15σ to 75σ in steps of 10σ. (e) CO 3–2 emission contours from Tang et al. (2017) overlaid on the HCO$^+$ J = 3–2 image. (f) HCN integrated intensity map with HCO$^+$ overlaid as black contours (natural weights). HCO$^+$ contour levels are 20σ to 40σ in steps of 1σ. The 5σ level is also shown. Interesting positions in the maps are labeled in white. Integrated line intensity maps were built by integrating velocity channels between ±2 and ±10 km s$^{-1}$. Beam sizes are shown in the bottom-left corner of each plot.

During these observations, the wideband correlator Wideband Express (WideX; Δν = 2 MHz) was used to cover the ∼2 GHz receiver band, and two correlator units providing a higher spectral resolution of ∼39 kHz were located at the frequencies of the HCO$^+$ J = 3–2 and HCN J = 3–2 lines, respectively. The region empty of emission channels was used to build the 1.12 mm continuum published by Fuente et al. (2017). The observations in A configuration were done in 2018 March, using the new correlator PolyFix, which provides a total band of ∼7.74 GHz with a spectral resolution of Δν = 2 MHz. In addition, higher spectral resolution Δν = 65 kHz chunks were located at the frequencies of the HCO$^+$ and HCN lines. All data from A and C configurations were resampled to a frequency resolution of 89 kHz and merged to build the A+C table of visibilities used to create the images shown in this Letter. In order to optimize the spatial resolution, we have applied uniform weighting to produce the HCO$^+$ J = 3–2 image. In the case of the HCN J = 3–2 line, we prefer to use natural weighting because the weaker line emission. Self-calibration was applied to improve the sensitivity and dynamical range. Data calibration and imaging were done using the package GILDAS$^6$/CLASS software.

3. Results

As Figure 1 shows, the integrated intensity maps of the HCO$^+$ J = 3–2 and HCN J = 3–2 lines unveil important differences in the distribution of the HCO$^+$ and HCN emissions in the radial and azimuthal directions. While HCN is only detected (above 5σ) in an annular ring that is spatially coincident with the dust ring (hereafter, outer ring), HCO$^+$ is detected in the outer ring and also features intense and compact emission toward the star position. Additionally, a bright HCO$^+$ bridge connecting the compact central source with the outer ring (labeled BR in Figure 1) is observed. To test whether the bridge is due to an elongation of the central emission along the beam major axis, we show in Figure 2 a comparison of the spatially integrated line profiles of HCO$^+$ at different positions. The line profile along the bridge (Figure 2(b)) is quite different from that of the central emission (Figure 2(a)): while the profile in the innermost region peaks at 6.7 km s$^{-1}$ (close to the system velocity), with an FWHM of 1.4 km s$^{-1}$, the line profile at the bridge location is two-peaked, with a redshifted wing at 7.3 km s$^{-1}$ with an FWHM of 0.8 km s$^{-1}$ and a blueshifted broad and fainter wing at ∼5.3 km s$^{-1}$. The difference in the line profiles shows that the emission seen at the location of the bridge is not the elongation by the beam of the emission from the inner disk, thus a feature on its own.

In Figure 1(e) we compare our HCO$^+$ J = 3–2 integrated intensity map with the CO J = 2–1 observations by Tang et al. (2017). The southwestern spiral arm observed in CO J = 2–1 overlaps with the position of the HCO$^+$ J = 3–2 bridge in its

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$^6$ See http://www.iram.fr/IRAMFR/GILDAS for more information about the GILDAS softwares.
emission in the outer ring follows quite well the dust emission with intensity variations $<2\sigma$ along it. This is in agreement with what we expect from two-fluid simulations (Fuente et al. 2017) in which the gas surface density is quite uniform along the ring, while large particles are still accumulated in the dust trap. We note that we measure an intensity contrast of a factor of $\sim3$ in the dust 1.12 mm continuum emission. In contrast, the HCN emission seems to follow the spatial distribution of large particles, with the most intense clump, LM1, being spatially coincident with the dust trap. In the eastern-half disk where the 1.12 mm continuum emission presents its minimum, the HCN emission seems to come from the external parts of the ring (see LM4 in Figure 1). Given the limited sensitivity of our maps it is important to note that LM2, LM3, and LM4 could be due to strong noise fluctuations. Although the HCO$^+$ and HCN are both high-density tracers, the two molecules present a different chemistry and are expected to come from different layers within the disk (Pacheco-Vázquez et al. 2015). HCN is known to be abundant in dense cold regions where CO and HCO$^+$ are frozen on grains (Fuente et al. 2018). In addition, the emission of HCO$^+$ might be optically thick toward the outer ring.

4. Discussion

4.1. Gas Inside the mm Dust Cavity

Low-resolution spectral observations of AB Aur are available from about 1 $\mu$m up to about 400 $\mu$m (Woitke et al. 2019). The detection of several O I, C II, C, OH, and ro-vibrational lines of CO and H$_2$ prove the existence of warm gas (Brittain et al. 2003; Bitner et al. 2007; Riviere-Marichalar et al. 2016). The origin (inner disk, outflow, gas filling the cavity) of these line emissions is uncertain because of the moderate angular and spectral resolutions of the observations. Based on observations of the [O I] 63 $\mu$m line, Riviere-Marichalar et al. (2016) concluded that part of the atomic oxygen emission is coming from the jet.

Interferometric (sub-)millimeter images provide insights into the gas and dust distributions. Out of all the molecular lines imaged with millimeter interferometers in AB Auriga (Piétu et al. 2005; Tang et al. 2012; Pacheco-Vázquez et al. 2016; Tang et al. 2017), only the high-resolution CO $J = 2$--$1$ image reported by Tang et al. (2017) and our HCO$^+$ $J = 3$--$2$ image show evidence of molecular emission within the cavity. These two lines present, however, different line profiles. Figure 2(a) shows integrated CO $J = 2$--$1$ and HCO$^+$ $J = 3$--$2$ spectra in the innermost region (see Figure 2(d)). The line profile of the HCO$^+$ line shows a narrow, $\Delta v = 1.4$ km s$^{-1}$ component at 6.7 km s$^{-1}$ on top of broad wings covering the $\sim0$--10 km s$^{-1}$ velocity range. Although the CO $J = 2$--$1$ line covers the same velocity range, its profile is flat-topped. As commented by Tang et al. (2017), the flat CO line profile can be due to self-absorption and spatial filtering effects. It should be noted that recent observations of CO $J = 3$--$2$ and HCO$^+$ $J = 3$--$2$ in AA Tau by Loomis et al. (2017) showed different spatial distribution of the HCO$^+$ $J = 3$--$2$, and CO $J = 3$--$2$ emissions, suggesting that they are indeed coming from different regions.

The poor knowledge of the physical conditions of the gas within the cavity ($r < 80$ au) makes it difficult to derive molecular abundances. Woitke et al. (2019) calculated a gas mass of $4.2 \times 10^{-4} M_\odot$ for the inner disk, with a column density of $N_H \sim 3 \times 10^{22}$ cm$^{-2}$ at $r \sim 40$ au. Assuming optically thin emission and that the HCO$^+$ $J = 3$--$2$ line is

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**Figure 2.** (a) Comparison of the spatially integrated line profile of CO $J = 2$--$1$ (blue) over the inner regions. The vertical dashed line displays the system velocity. (b) Spatially integrated HCO$^+$ line profile over the bridge position. (c) Comparison of spatially integrated HCN and HCO$^+$ line profiles over the outer ring. All the spectra have been scaled to their maximum values to allow for an easy comparison. (d) Location of the regions used to obtain the integrated spectra are shown as a black ellipse (innermost regions), a red ellipse (bridge), and white circles (ring).
thermalized at $T_k = 150 \text{ K}$ (Tang et al. 2017), we derive $N(\text{HCO}^+) = 3 \times 10^{13} \text{ cm}^{-2}$, i.e., an HCO$^+$ abundance of $\sim 10^{-9}$ within the cavity, which is compatible with typical values in photo-dissociation regions (see, e.g., Fuente et al. 2003; Ginard et al. 2012; Goicoechea et al. 2017). The HCO$^+$ abundance might be larger if the HCO$^+$ $J = 3–2$ emission is optically thick.

4.2. HCO$^+$/HCN: A Chemical Tool

Dramatic chemical segregation is found in the radial direction and along azimuth within the AB Aur disk. The absence of large grains within the cavity allows the UV irradiation from the star to penetrate through it and photo-dissociate molecules. Very few species are expected to survive in highly irradiated gas. H$_2$ and CO are abundant enough to self-shield the stellar radiation (see, e.g., Sternberg & Dalgarno 1995). In addition, small hydrides (CH, CH$^+$, NH), reactive ions (CO$^+$, HOC$^+$), and simple oxygenated species such as OH and HCO$^+$ are detectable in the highly irradiated layers of photon-dominated regions (Fuente et al. 2003; Goicoechea et al. 2017). Because it is easily observable at millimeter wavelengths, HCO$^+$ is an excellent candidate to investigate the gas dynamics within the cavities of nearby transition disks.

Our observations suggest that the HCO$^+$/HCN intensity ratio is a useful chemical tool in determining the structure of transitional disks. In the case of unresolved disks, a high HCO$^+$/HCN intensity ratio might be associated with the existence of inner dust cavities full of dense gas. We note that, together with AB Aur, HD 142527 and AA Tau were the disks with a higher HCO$^+$/HCN $J = 3–2$ ratio in the compilation of Pacheco-Vázquez et al. (2015). Both systems show filamentary gas emission through their dust cavities (Casassus et al. 2013; Loomis et al. 2017). The other disk with a high ratio, GM Aur, has not been studied in detail. This result is also in line with recent results by Alonso-Albi et al. (2018) toward the Herbig Be star R Mon.

4.3. Gas Kinematics

We show in Figure 3(a) the first moment map of HCO$^+$ emission. The outer parts of the disk resemble those of a Keplerian disk. However, twisted isophotes are observed toward the center ($r < 0.07$). The aforementioned twisting can be reproduced by two misaligned Keplerian disks as proposed by Hashimoto et al. (2011). A radial outflow would produce a similar effect (Rosenfeld et al. 2014). We adopt the misaligned disks as the most plausible explanation, as it is consistent with near-IR observations by Hashimoto et al. (2011). In Figure 3(b), we show the residual map that results from subtracting a two Keplerian disks model from the HCO$^+$ first moment map. The model consists of an outer disk extending from 350 to 45 au, with $i = 26^\circ$ and PA = 37°, and an inner one extending from 45 au inward with $i = 43^\circ$ and PA = 65° (Hashimoto et al. 2011), around a 2.4 $M_\odot$ star, and the final image is convolved with the observational beam. This simplistic model provides a reasonable fit across the disk, except in the southwestern region, where strong residuals are observed. Visual inspection of Figure 3(a) shows that there is an anomaly (blue circle) in the velocity field that is spatially coincident with the bridge (BR, Figure 3(b)). This anomaly is due to high-velocity winds in the line profile of HCO$^+$ at the bridge position (see Figure 2(b)). The redshifted peak is compatible with Keplerian rotation, while the blueshifted one requires a different mechanism, most likely infalling gas. To test the possibility that the blueshifted wing is tracing infalling material, we built a pure free-falling velocity field following equation

$$V_{\text{free-fall}} = \sqrt{2GM_\odot \times \left(\frac{1}{r} - \frac{1}{r_{\text{start}}}\right)}$$

where $r_{\text{start}}$ is the starting position for free-fall accretion, and we adopted $r_{\text{start}} = 120$ au (accretion starts at the inner edge of the dust ring, $r \sim 0.07$). We assumed that infall stops at 40 au. Cuts in the first-moment map, and in our convolved models are shown in Figure 3(c). The free-falling model has a velocity of 5.5 km s$^{-1}$ at the bridge position, compared to the 5.3 km s$^{-1}$ derived from the Gaussian fit. Therefore, some of the material in the bridge seems to be infalling at a velocity close to free-fall. Smaller velocities, such as the speed of sound, which is typically 0.05–0.1 times the Keplerian velocity, cannot account for the blueshifted component. Assuming that this component is due to accretion, we derive a mass accretion $3 \times 10^{-8}$ to $3 \times 10^{-7}$ $M_\odot$ yr$^{-1}$ (for $X(\text{HCO}^+) = 10^{-9}$ to $10^{-8}$), comparable to a value of $1.2 \times 10^{-7}$ $M_\odot$ yr$^{-1}$ by Salyk et al. (2013).
Radial inflows through dust cavities have been invoked before to explain different features observed in a few protoplanetary disks, such as gas and dust streamers and twisted isophotes (Casassus et al. 2013; Dutrey et al. 2014; Perez et al. 2015; Zhang et al. 2015; Loomis et al. 2017; Mendigutía et al. 2017; Walsh et al. 2017). In particular, Zhang et al. (2015) proposed radial inflows to explain absorption features observed in CO ro-vibrational lines in AA Tau, with material moving at velocities close to free-fall in regions between the inner and outer disk. The presence of gap-crossing radial inflows could explain the high accretion levels derived for some transitional disks, such as those observed in AB Aur (Garcia Lopez et al. 2006; Salyk et al. 2013). A compact and collimated bipolar jet was detected by Rodríguez et al. (2014) in the continuum at 7 mm, suggesting the existence of a disk-jet system. In order to sustain it, gas must flow through the cavity and reach the inner regions of the system, otherwise accretion would drain the inner disk on very short timescales.

We cannot discard the possibility that the non-Keplerian component observed along the bridge is due to gas out of the disk plane, in which case, depending on the exact location of the bridge, it might be interpreted as an inflow or an outflowing stream.

Previous work by this team proposed that the asymmetric dust ring is caused by dust trapping in a decaying gas vortex formed at the outer edge of the gap carved by a massive planet, coincident with the position of the bridge (Fuente et al. 2017). Higher-spatial resolution observations, with facilities such as ALMA, are needed to understand the connection between the HCO+ bridge in the cavity and the putative planet responsible for the outer dust ring.

5. Summary and Conclusions

We used the NOEMA interferometer to map with high angular resolution the HCO+ and HCN J = 3–2 lines. Based on these interferometric data, we explored the chemistry and dynamics of the molecular gas component in the AB Aur disk, and its relationship with the decaying gas vortex found in it. We detected ring-like emission in HCN, spatially coincident with dust emission. HCO+ shows a ring-like structure in the outer regions, plus a compact source at the center. We suggest that the HCO+ / HCN ratio is a useful tool to discern the presence of dense gas in dust cavities.

Our most prominent result is the detection of a filamentary HCO+ emission structure that connects the outer disk with the inner regions. A simple model consisting of two misaligned Keplerian disks with an infall component along the bridge can reproduce our observations, suggesting the presence of active accretion within the dust cavity. Yet, alternative explanations involving gas out of the disk plane cannot be ruled out. The possible connection of the observed bridge with a planet formation scenario requires further research.

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