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Letter to the Editor

Cavities in inner disks: the GM Aurigae case⋆

A. Dutrey[1], S. Guilloteau[1], V. Piétu[2], E. Chapillon[1,2], F. Gueth[2], T. Henning[3], R. Launhardt[3], Y. Pavlyuchenkov[3], K. Schreyer[4], and D. Semenov[3]

[1] LAB, UMR 5804, Observatoire de Bordeaux, 2 rue de l'Observatoire, 33270 Floirac, France
e-mail: [Anne.Dutrey;Stephane.Guilloteau;edwige.chapillon]@obs.u-bordeaux1.fr
[2] IRAM, 300 rue de la Piscine, 38400 Saint Martin d'Hères, France
e-mail: [pietu;gueth]@iram.fr
[3] Max-Planck-Institut für Astronomie, Königstuhl 17, 69117 Heidelberg, Germany
e-mail: [henning;pavyar;semenov]@mpia.de; rl@mpia-hd.mpg.de
[4] Astrophysikalisches Institut und Universitäts-Sternwarte, Schillergässchen 2-3, 07745 Jena, Germany
e-mail: martin@astro.uni-jena.de

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ABSTRACT

Context. Recent modeling based on unresolved infrared observations of the spectral energy distribution (SED) of GM Aurigae suggests that the inner disk of this single TTauri star is truncated at an inner radius of 25 AU.

Aims. We attempt to find evidence of this inner hole in the gas distribution, using spectroscopy with high angular resolution.

Methods. Using the IRAM array, we obtained high angular resolution (∼1.5′′) observations with a high S/N per channel of the ^{13}CO $J = 2{-}1$ and C^{18}O $J = 2{-}1$ and of the ^{13}CO $J = 1{-}0$ lines. A standard parametric disk model is used to fit the line data in the Fourier-plane and to derive the CO disk properties. Our measurement is based on a detailed analysis of the spectroscopic profile from the CO disk rotating in Keplerian velocity. The millimeter continuum, tracing the dust, is also analyzed.

Results. We detect an inner cavity of radius 19 ± 4 AU at the 4.5σ level. The hole manifests itself by a lack of emission beyond the (projected) Keplerian speed at the inner radius. We also constrain the temperature gradient in the disk.

Conclusions. Our data reveal the existence of an inner hole in GM Aur gas disk. Its origin remains unclear, but can be linked to planet formation or to a low mass stellar companion orbiting close to the central star (∼5−15 AU). The frequent finding of inner cavities suggests that either binarity is the most common scenario of star formation in Taurus or that giant planet formation starts early.

Key words. stars: formation – ISM: molecules – stars: circumstellar matter – radio lines: stars – stars: individual: GM Aurigae

1. Introduction

Since the discovery of its rotating disk by Koerner et al. (1993), the TTauri star GM Auriga has been intensively observed. Located in the Taurus-Auriga cloud, at a distance of 140 pc, this star has a spectral type K7 and its age is estimated to be 3 Myr. Dutrey et al. (1998, hereafter Paper I) have used the IRAM array to map the disk in ^{12}CO $J = 2{-}1$ and found that the disk extends up to 550 AU and is in Keplerian rotation. Using these CO data, Simon et al. (2000) have derived a dynamical mass for the star of 0.84 ± 0.05 $M_\odot$. In the meantime, several groups have analyzed its spectral energy distribution (SED) in the infrared (IR), around 5−20 μm, which presents a relatively pronounced dip. Koerner et al. (1993) suggested that the dip was due to a lack of dust at a few AU from the star, or a gap created by a protoplanet or a brown dwarf orbiting the star. This first estimate of the hole radius was ∼0.4 AU and was based on a simple flared accretion disk model fitted to the IR SED. More recently, Rice et al. (2003) used an SPH code to model the IR SED when a planet is migrating in the inner disk. They found that a hole of 4 AU can be created by a planet of about 2 M_J orbiting at 2.5 AU from the central star. Bergin et al. (2004) used a refined model (Calvet et al. 2002) which takes into account the wall at the inner radius, illuminated by the star. Their SED modelling implies an inner radius of the order of 6 AU. Finally, taking in consideration new Spitzer data, Calvet et al. (2005) modelled the SED of GM Auriga with a better spectral resolution in the IR and they found a larger cavity of radius of the order of 24 AU.

So far, this is the largest cavity derived from the modelling of IR SEDs. In the case of DM Tau, LkCa15 or TW Hya, Bergin et al. (2004) and Calvet et al. (2002) have derived holes of radii around 3−5 AU. However, SED modeling only constrains the dust content. CO rovibrational emission from the inner AU has been detected by Salyk et al. (2007). This indicates the existence of a low mass gaseous inner disk (∼0.3 $M_\oplus$ if it extends up to 5 AU). Finding whether the gas follows the large scale dust pattern or not is important to understand the origin of these cavities, and mm interferometric observations are well suited for this.

We report here observations of several CO lines in the disk of GM Aur to test the presence of the inner gas hole. Observations and results are described in Sect. 2 and the analysis in Sect. 3 The implications are discussed in Sect. 4 before our conclusions.

2. Observation and results

The first observations of the CO isotopologues were performed in winter 1996/1997. The 4 antennas with dual frequency

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Table 1. Best parameters for GM Aurigae.

Molecules Transitions	^{13}CO J = 1–0 & J = 2–1	C^{18}O J = 2–1	^{12}CO new fits J = 2–1	^{12}CO old fits J = 2–1
V_{LSR} (km s^{-1})	5.64 ± 0.01	5.64 ± 0.05	5.62 ± 0.02	5.62 ± 0.03
Orientation, PA (°)	144 ±1	[145]	[145]	141 ± 2
Inclination, i (°)	49.4 ±1.1	[50]	[51.5]	56 ±2
Velocity law: $V(r) = V_{100}(\frac{r}{100\ \mathrm{AU}})^{-v}$				
Velocity, V_{100} (km s^{-1})	2.97 ±0.04	[2.97]	[2.97]	2.78 ± 0.1
Velocity exponent, v	0.51 ± 0.01	[0.50]	[0.50]	0.5 ± 0.1
Stellar mass, M_* ($M_\odot$)	1.00 ± 0.05	[1.00]	[1.00]	0.84 ± 0.05
CO Surface density, (cm^{-2})	26 ± 4 × 10^{15}	2.3 ± 0.2 × 10^{15}	1.6 ± 1.1 × 10^{18}	2.85 × 10^{18}
Exponent p	2.3 ± 0.15	2.9 ± 0.3	3.8 ±0.4	[1.57]
Inner radius R_{in}, (AU)	13 ± 4	31 ± 6	45 ± 15	[1]
Outer radius R_{out}, (AU)	445 ± 15	400^{+200}_{-50}	630 ± 25	525 ± 20
Temperature, (K)	23 ± 2	[24]	32 ± 2	37 ± 2
Exponent q	0.33 ± 0.07	[0.33]	0.45 ± 0.05	0.64 ± 0.06
dV (km s^{-1})	0.31 ± 0.02	[0.30]	0.33 ± 0.03	(0.17 ± 0.04)*
Scale height, (AU)	[16.5]	[16.5]	[16.5]	17
Exponent h	[1.25]	[1.25]	[1.25]	1.18

Column (1) contains the parameter name. Columns (2, 3) indicate the parameters derived from ^{13}CO (J = 1–0 and J = 2–1 simultaneous line fit), C^{18}O and ^{12}CO J = 2–1 lines. Column 4 is from Dutrey et al. (1998). The values quoted in [] were fixed. Note that the PA is that of the disk axis, see Piétu et al. (2007) for a description of the convention for the PA and the inclination i. (*) Not including the thermal broadening contrary to the others, see Piétu et al. (2007). The model and its parameters are described in Piétu et al. (2007).

receivers allowed simultaneous observations of ^{13}CO J = 1–0 in the 3 mm band and C^{18}O J = 2–1 in the 1.3 mm band. The rms phase noise was around ~20–25° at 2.7 mm and 40–50° at 1.3 mm. The flux calibration was based on the regular monitoring of the flux density of the quasars 0415+379 and 0528+134 and on MWC 349 (see IRAM flux report 13). The baseline range was 15 to 280 m.

New simultaneous observations of ^{13}CO J = 2–1 and C^{18}O J = 2–1 were carried out in the context of the CID (Chemistry In Disks) project with 6 antennas using the new 1.3 mm receivers on Nov. 1st, 2007. The source was observed in the C configuration by the interferometer for ~8 h (max baseline 100 m). The *total on-source* observing time dedicated to GM Aur was about 6 h. The rms phase noise was between 20 and 40° at 1.3 mm.

All data were reduced using the GILDAS[1] software supported at IRAM. All data were calibrated using the latest (2007) version of this reduction package.

As the data are separated by about 10 years, we corrected for the proper motion of GM Aur before combining the data set. The apparent positions (derived from the continuum data) between the 1996/97 data and the 2007 one is $\Delta\alpha$ = 0.24″, $\Delta\delta$ = −0.24″, with formal errors around 0.03″, but the astrometric accuracy is only about 0.05″ in each direction. From Ducourant et al. (2005), the proper motion of GM Aur is (3 ± 6, −26 ± 6) mas/yr. Given the uncertainties, and following the arguments of Guilloteau et al. (2008), we thus used the representative value of (12, −20) mas/yr for the proper motion before combining the data, but checked that the exact value has no influence on the results presented in Table 1. Figure 1 presents the final deconvolved images. The CO isotopologue emission follows the pattern of a rotating disk, in very good agreement with the ^{12}CO J = 2–1 data from Dutrey et al. (1998).

[1] See http://www.iram.fr/IRAMFR/GILDAS for more information about the GILDAS softwares.

3. Analysis and disk properties

With a linear resolution of about 200 AU, revealing the existence of a hole of ≈40 AU diameter cannot be done directly. A hole of radius R manifests itself by a small deficit of emission in the central beam and by a lack of emission at velocities above $\sqrt{GM_*/R}\sin i$ (Dutrey et al. 1994; Goto et al. 2006), i.e. 5.1 km s^{-1} in our case for a 20 AU radius hole. However, with the integration times used, the expected signal above these velocities is only 2σ in each transition. Only a global fit of a parametric disk model to the measured visibilities can optimally use all the available data and reveal the inner hole.

An accurate representation of the mm continuum emission is required, as an improper value would contaminate the line wings and affect the (gas) inner radius determination. We have modeled the disk emission using the same method as Piétu et al. (2007), with simultaneous fitting of the combined data for the two transitions of ^{13}CO, and separate fits for the ^{12}CO and C^{18}O J = 2–1 lines. In each case, we used a simultaneous fit of the continuum and line emission, which is the best method to properly estimate the relative contributions of these two emission processes. We also checked that the simplified method of subtracting the continuum from the line emission essentially gave the same result (see Piétu et al. 2007, for details). We also took care to properly adapt the gridding to the numerical problem by using a pixel size of 0.6 AU in the inner ~40 AU of the disks (see Piétu et al. 2007, for a description of the grid). For the lower S/N C^{18}O and ^{12}CO data, we fixed the orientation, the inclination, the systemic velocity and the stellar mass to the best value derived from the ^{13}CO data. The results are presented in Table 1. All three best fits indicate the presence of an inner hole, of radius 13 to 45 AU, but at best at the 3–4σ significance level. At this level, the errorbars are asymmetric and care must be taken in interpreting them. We explored the χ^2 values as a function of inner radius by adjusting all other parameters simultaneously for each R_{in}. The curves indicate R_{in} < 5 AU is excluded at 3σ for the ^{13}CO and C^{18}O data, and only at 2σ by the ^{12}CO data.

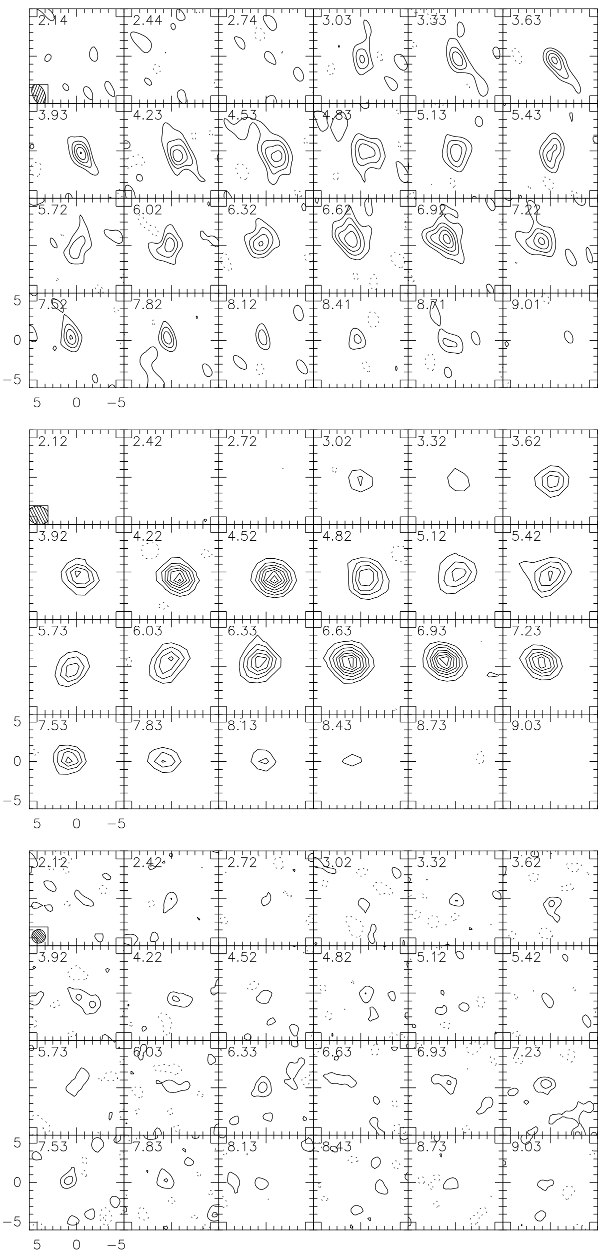

Fig. 1. *Top*: ^{13}CO $J = 1{-}0$ data: contours levels are 0.02 Jy/beam (1.6σ or 0.5 K) starting at −0.04 Jy/beam. Beam size is 2.67″ × 1.56″, PA = 23°. *Middle*: channel maps of the ^{13}CO $J = 2{-}1$ data: contours levels are 0.1 Jy/beam (2.8σ or 0.4 K) starting at −0.2 Jy/beam. Beam size is 2.81″ × 2.25″, PA = 72°. *Bottom*: channel maps of the C^{18}O $J = 2{-}1$ data, contours levels are 0.04 Jy/beam (1.7σ or 0.34 K) starting at −0.120 Jy/beam. Beam size is 1.75″ × 1.74″, PA = −94°.

Both the disk inclination and the position angle are in agreement with the previous CO results from Paper I. Besides the existence of an inner hole which was not previously searched for, the new results differ in some ways from the original analysis: i) the stellar mass; ii) the kinetic temperature; iii) the surface density law and outer radius. The stellar mass derived from the new data, $M_* = 1.00 \pm 0.05\ M_\odot$, is slightly above (at 3σ) the value quoted by Simon et al. (2000), 0.84 ± 0.05 $M_\odot$. The newer value is likely more accurate since it takes into account new data and a better data reduction, and, most importantly, the effect of an inner radius. In the earlier analysis, $R_{\rm in}$ was fixed to 1 AU. Due to inner truncation, the high velocity wings were suppressed, and as a consequence the apparent line-width was lower. The inclination was not affected (as it is mostly constrained by the apparent size at the systemic velocity), so this mimicked a slightly lower stellar mass. The only other star in the Simon et al. sample which could be affected by a similar effect is LkCa15, which has already been reanalyzed by Piétu et al. (2007).

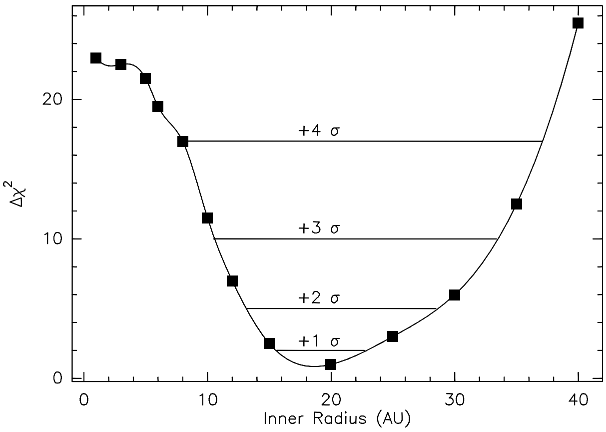

Fig. 2. χ^2 distribution versus inner radius when summing the individual χ^2 obtained for all the observed isotopologues. The inner radius is truncated at 19 ± 4 AU, the detection being at the 4.5σ level. Note that the error bars are asymmetric.

All other parameters are stable with respect to the value of the inner radius within the range 20−45 AU. We find a lower kinetic temperature (T_{100}) with a flatter radial index (q) and a larger outer radius. In the earlier analysis, we assumed a purely hydrostatic scale height. As explained by Piétu et al. (2007), this causes a positive bias in the kinetic temperature. In Paper I, we assumed a shallower surface density law by fixing $p = 1.5$. Here we fitted this dependence and find $p = 3.8$. As a compensation, the disk outer radius was smaller.

Although the three fits give somewhat different values for $R_{\rm in}$, combining them allows us to better constrain the size of the inner hole. Figure 2 shows the global χ^2 distribution as a function of the gas inner radius $R_{\rm in}$. This χ^2 has been obtained by summing the individual χ^2 obtained on the various isotopologues of CO ($\chi^2 = \chi^2(^{12}{\rm CO}) + \chi^2(^{13}{\rm CO}) + \chi^2({\rm C}^{18}{\rm O})$). This procedure is justified as the common parameters for all transitions (rotation velocity, position angle and inclination) have negligible influence on the determination of $R_{\rm in}$. The inner disk appears truncated at an inner radius of 19 ± 4 AU. Despite a limited angular resolution of ~200 AU, the spectroscopic information allows us to estimate the inner disk truncation. Figure 2 also illustrates the asymmetry of the error bars on $R_{\rm in}$.

From a combined fit of all continuum data, using the temperature derived from ^{12}CO, we find from the dust emission $p = 1.3 \pm 0.2$, $R_{\rm out} = 250 \pm 20$ AU. The emissivity spectral index is $\beta = 0.80 \pm 0.03$ (to which an 0.1 uncertainty must be added due to calibration precision), typical of such objects. The surface density at 100 AU is about 1 g cm^{-2} ($\Sigma({\rm H_2}) \simeq 3 \times 10^{23}$ cm^{-2}), and the disk mass is ~0.017 $M_\odot$ using a mass absorption coefficient of 0.03 cm^2 g^{-1} (of gas+dust) at 230 GHz.

The disk parameters can be compared to those of other TTauri disks such as LkCa15 or DM Tau which have been studied in a similar way by Piétu et al. (2007). At 100 AU, the surface density deduced from the optically thinner ^{13}CO data is similar to that of LkCa15, and lower than that of DM Tau by a factor of 10. The ratios [^{12}CO/^{13}CO] ≈ 60 and [^{13}CO/C^{18}O] = 10 are consistent with standard isotopic abundances, but the fitted slopes p

differ between ^{12}CO and ^{13}CO. Comparing to the H_2 surface density of 3×10^{23} cm^{-2}, the CO depletion at 100 AU is of the order of 20. Both ^{13}CO and ^{12}CO indicate a temperature of 23−32 K at 100 AU, and a slope $q \simeq 0.40$. The vertical temperature gradient is not strong, a situation reminiscent of that of the LkCa15 disk which also exhibits a large inner cavity. The outer radius in the rarer CO isotopologues also appears significantly smaller than in ^{12}CO; this is likely due to selective photodissociation (Dartois et al. 2003).

4. Discussion

Progress in mm/submm interferometers have allowed investigators to reveal cavities in an increasing number of objects: a 100 AU radius in AB Aur (Piétu et al. 2005), and ∼40 AU radius in LkCa 15 (Piétu et al. 2006), HH 30 (Guilloteau et al. 2008) and LkHα 330 (Brown et al. 2008).

Among the possible explanations for such cavities, photoevaporation is very unlikely for GM Aur, as the surface density at the cavity edge is still quite large (Alexander et al. 2006). The most probable explanation is tidal disturbance by a low-mass star or a planet.

The size of the hole places constraints on the distance of the companion, which would be at about 3−8 AU from the primary (Artymowicz et al. 1991). No companion as yet been discovered around GM Aur. The total mass of GM Aur is $1.00 \pm 0.05\ M_\odot$, and the effective temperature of the star 4060 K. Using the Baraffe et al. (1998) tracks, we find that the primary is too warm to have a mass lower than $0.7\ M_\odot$, and thus the companion should not exceed $0.3\ M_\odot$ (H magnitude would be <9.4, leading to a $\Delta H > 0.8$). This is somewhat different from the case of Coku Tau/4, a weak line TTauri star surrounded by a transition disk (D'Alessio et al. 2005) which has recently been found to be an equal mass binary surrounded by a circumbinary disk (Ireland & Kraus 2008).

Another possibility would be an inner planetary system of one or more planets in the cavity, as for TW Hya (Setiawan et al. 2008). Following Takeuchi et al. (1996), the half-width w of a gap can be estimated from: $w = 1.3\, a\, A^{1/3}$ where A is the strength ratio of tidal to viscous effects and is given by $A = (M_p/M_*)^2/(3\alpha(h/r)^2)$. Table 1 indicates $h/r \simeq 0.1$, $M_* \simeq 1\ M_\odot$, and assuming $\alpha \sim 0.01$, a planet of mass $M_p \simeq 0.005\ M_\odot$ at a distance $a \simeq 15$ AU, we find $w \simeq 8.5$ AU. Hence a ∼5−10 Jupiter mass planet orbiting at 15 AU would be sufficient to open the GM Aur cavity.

Contrary to LkCa 15, the hole is clearly observed in the infrared SED as a pronounced dip. This requires a density contrast with an opacity drop by several orders of magnitude. At 10 μm and 20 AU, we can extrapolate a dust opacity of the order of ∼20−100, comparing with the value of $\tau \simeq 0.002$ derived by Calvet et al. (2005) inside the cavity, we get a contrast of the order $\sim 10^4 - 10^5$. This suggests that the planet is old enough to have had time to fully evacuate the dust and gas. Varnière et al. (2006) have modelled the viscous evolution of a disk where a Jupiter-like planet is embedded in the inner disk. They find that a density contrast of order $\sim 10^4 - 10^5$ between the inner hole and the surrounding disk requires about 6000−10 000 orbits to be reached (see their Figs. 1 and 4) assuming a 7 Jupiter mass planet. For GM Aur and an orbit radius of 15 AU, this corresponds to 0.5−0.6 Myr.

This is about one fifth of the assumed age of the disk/star system. Taking into consideration the time needed to form a "massive" core planet of 5−10 Jupiter mass (Lissauer & Stevenson 2006), this suggests that planet formation may have started relatively early, likely in the Class I phase, at least in this system.

5. Summary

We have observed the GM Aur gas disk in ^{13}CO $J = 1{-}0$ and $J = 2{-}1$ and C^{18}O $J = 2{-}1$ with the IRAM array at medium angular resolution. The main results are the following:

- We report the dynamical detection of a central hole of radius 20 AU which is likely due to the formation of a few Jupiter-mass planet (∼5−10 M_J) or a very low mass-star (≲0.3 $M_\odot$).
- Contrary to the cavity detected in LkCa15, the hole is almost devoid of dust since it is also clearly observed in the IR SED. If the cavity is due to planet formation, this suggests that planet formation should start very early, likely in the Class I phase.
- The disk structure of GM Aur is very similar in surface density and temperature to that of the LkCa15 disk which also exhibits a central cavity. In particular, the vertical temperature gradient at 100 AU is not very strong.

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