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GG Tau: The Ringworld Revisited

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Abstract. GG Tau is a textbook example of a binary system. The circumstellar material around GG Tau is divided in several distinct regions: 1) small, low mass, circumstellar disks, detected in the near-IR and mm domain, 2) a well defined ring, of inner radius 180 AU, detected in the mm domain and in scattered near-IR light, 3) a more extended, colder disk detected in the ^{13}CO(2-1) and ^{13}CO(1-0) lines. Recent observations of the ^{12}CO(2-1) clearly show this extended disk, but also reveal a fourth component of the circumstellar material: (relatively) diffuse and hot gas in the tidally unstable region. Estimate of the gas content suggest this material may be feeding the inner disks at about $10^{-6}\,M_\odot$/yr.

Discovered by Leinert et al. (1991), GG Tau has become the classical example of a young binary system. Although GG Tau was known as featuring the second strongest mm emission from a T Tauri star (just after HL Tau, Beckwith et al. 1990), it was not before 1992 that it attracted the astronomer's eyes following two independent discoveries. First, Simon and Guilloteau (1992) discovered that the mm emission from GG Tau was heavily resolved with the IRAM interferometer, with an apparent size of about $2''$. Second, Skrustkie et al. (1993) discovered CO emission from GG Tau with the 45-m telescope. Follow up observations with the Nobeyama array in CO showed a velocity gradient suggestive of rotation (Kawabe et al. 1993). Complete evidence for Keplerian rotation was revealed by the observations of the ^{13}CO(1-0) line with the IRAM interferometer (Dutrey, Guilloteau and Simon, 1994, hereafter DGS94).

From the $\sim 2''$ resolution continuum image, DGS94 also showed that the continuum emission from GG Tau displayed a hole in the middle, rather than being centrally peaked as in single T Tauri stars. By modeling the aspect of the continuum and line emission, DGS94 concluded that the radius of the hole was about 180 AU, while the circumbinary disk extended out to 600 AU or more. DGS94 also pointed out that the continuum and ^{13}CO images were inconsistent with a "classical", but truncated, power law density distribution. Instead, they inferred that most of the mass was confined in a ring-like structure around the inner hole surrounded by a less dense outer disk. Comparison of the ^{13}CO and continuum suggested CO and its isotopomers were depleted by a factor of 20 compared to the standard abundances in the Taurus molecular cloud. The kinematic pattern obtained from ^{13}CO(1-0) was consistent with Keplerian rotation around a central mass of $1.2\,M_\odot$. The inclination derived from both continuum and ^{13}CO was about $35 - 40°$.

Subsequent near-infrared observations with adaptive optics at the CFHT by Roddier et al. (1996) revealed the ring in scattered light. The images fully

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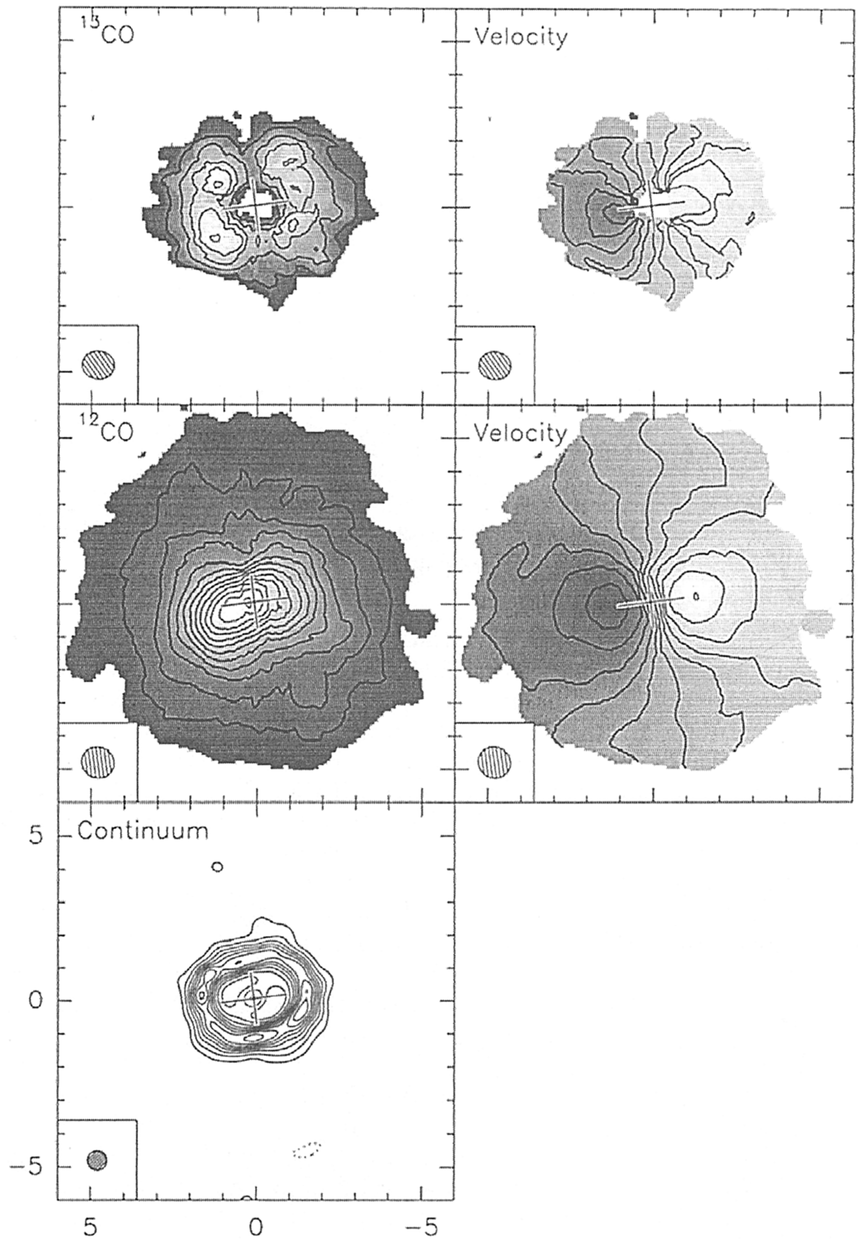

Figure 1. Images of the GG Tau circumstellar environment. Top: Integrated intensity map of ^{13}CO(2-1) and derived velocity map. Middle: same for ^{12}CO(2-1) but with a $\sim 1''$ resolution. Bottom: combined continuum image with a $0.6''$ resolution. Coordinates are in $''$. The cross indicates the centroid of the disk and the direction of the major and minor axis.

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resolved for inner hole for the first time and revealed the inner disks. These data confirmed the inner radius of 180 AU for the ring and showed that the stars were not located at the center of the ring as seen in near infrared, but slightly offset. Roddier et al. (1996) interpreted this offset as an indication for an elliptical ring, in which the stars are expected to be located at the ellipse focus.

With the installation of 1.3 mm receivers at the IRAM Plateau de Bure interferometer, it became possible to perform sub-arcsecond angular resolution observations with sufficient sensitivity in the ^{13}CO(2-1) line. Figure 1 shows the integrated intensity map (top left), velocity map (top right), and continuum image (bottom) obtained by Guilloteau, Dutrey and Simon (1999, GDS99). While the continuum emission is obviously confined to a ring, the ^{13}CO(2-1) line emission extends out to several hundred AUs from the star, confirming the initial interpretation of DGS94. The high angular resolution and sensitivity allow GDS99 to perform a χ^2 analysis, similar to that performed for DM Tau by Guilloteau and Dutrey (1998). This allows proper error determinations for the disk and ring parameters (see GDS99, their Table 2). In particular, the velocity pattern is found to be essentially Keplerian, and the dynamical mass derived is $1.28 \pm 0.07\,M_\odot$, for a distance of 140 pc. The ring, located within 180 and 260 AU, contains 70 % of the total mass and has sharp edges.

The angular resolution in the continuum is now sufficient to resolve the ring, and the high sensitivity allowed the first detection of the **inner** disks in the mm range. Using dust opacity appropriate for circumstellar disks, GDS99 indicate a lower limit to the mass of $\simeq 10^{-4}\,M_\odot$ and a lower radius limit of $\simeq 4$ AU for the inner disks. In this image, the inner disks and circumbinary ring are approximately centered, contrary to the IR image of Roddier et al. (1996). Using the inner disks to register the two images, the comparison between the two images indicates that the IR ring is offset by $\simeq 0.25''$ northward of the radio ring. GDS99 interpreted this offset as a result of the finite thickness of the ring combined with the large difference in optical depth between 2μm and 1.3 mm. This interpretation has been subsequently confirmed by the optical polarimetry images obtained with the HST by Silber et al. (2000) (see also Ménard, this conference). The required thickness to obtain the apparent shift is large (120 AU). This is ~ 3.5 times the scale height (32 AU) derived from the temperature measured in ^{13}CO(2-1), consistent with an expected near-IR / visible optical depth of order 100 (GDS99). The temperature of the ring is large compared to that of the surrounding disk, but both values are consistent with what is expected since the inner edge of the ring is heated by direct light from the stars and inner disks (GDS99).

Observations of GG Tau in ^{12}CO(2-1) were performed in the winter 1998-1999. Figure 1 show the integrated intensity (middle left) and velocity (middle right) maps. Comparison with the ^{13}CO data reveal two differences: a) ^{12}CO is detectable much further out, up to 800 AU. This is expected since it is 60 times more abundant than ^{13}CO, b) there is detectable ^{12}CO(2-1) emission from **within** the ring. There are a priori three possible explanations for the ^{12}CO(2-1) emission from within the ring: 1) CO from the inner disks, 2) CO from an outflow emanating from one of the two stars, 3) CO within the tidally unstable region between the inner disks and the ring. Option 1 is not consistent with the apparent size of the emission, since the inner disks are expected to be

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smaller than about 20 AU. Option 2 is unlikely, because the kinematic pattern of the CO emission follows the general rotation curve. Hence we are left with option 3. The detection of ^{12}CO, combined with the upper limit in ^{13}CO and in continuum, allows us to constrain the mass contained within the ring.

The determination of the gas parameters in the tidally unstable region is a difficult task, because of the presence of the ring and large outer disk coupled to the marginally sufficient angular resolution. We proceed in two steps, first subtracting the best model of the GG Tau ring, as derived from the ^{13}CO data (see GDS99 Table 2), and noting that to first order, the ^{12}CO data confirm these values. The residual image has been analyzed with (yet another) "classical" Keplerian disk model. Preliminary results from this analysis suggest that:
1) The position angle of the CO emission is different from that of the outer disk ($220 \pm 10°$ instead of 187°). The inclination also appears somewhat lower ($25 \pm 3°$ instead of 37°).
2) The CO gas fills a significant fraction of the gap (outer radius > 120 AU).
3) The CO gas is almost optically thin but warm (temperature $\simeq$ 200 K).
A more thorough presentation will be given in Guilloteau et al. (2001, in prep.). The first two points suggest a significant distortion of the disk pattern in the tidal region, which is not unexpected since numerical simulations show that streamers of gas should form.

The last point is in agreement with the fact that ^{13}CO was not detected. If we further assume that the CO depletion is similar to that in the disk+ring (~ 20), the implied gas mass is $6\,10^{-4}\,M_{\odot}$. Since the orbital timescale is on the order of a few 100 years, this gas content may be feeding the inner disks with an accretion rate of $\simeq 10^{-6}\,M_{\odot}$/yr. This would be sufficient to replenish the inner disks. There are obviously many uncertainties affecting this number. Note however that a direct measurement of the H_2 density may be possible. With the above values, the H_2 density in the gap plane is only about 10^7 cm^{-3}. This value indicates that, if molecules like HCO^+, CN or HCN exist in the tidal gap like in the ring (Dutrey, Guilloteau and Guélin, 1997), a direct estimate of the density may be possible from constraints on the molecular line excitation.

References

Beckwith, S. V. W., Sargent, A. I., Chini, R. S., Guesten, R. 1990, AJ, 99, 924
Dutrey, A., Guilloteau, S., Guélin, M. 1997, A&A, 317, L55
Dutrey, A., Guilloteau, S., Simon, M. 1994, A&A, 286, 149 (DGS94)
Guilloteau, S., Dutrey, A. 1998, A&A, 339, 467
Guilloteau, S., Dutrey, A., Simon, M. 1999, A&A, 348, 570 (GDS99)
Kawabe, R., Ishiguro, M., Omodaka, T., et al. 1993, ApJ, 404, L63
Leinert et al. 1991, A&A, 250, 407
Roddier, C., Roddier, F., Northcott, M. J., et al. 1996, ApJ, 463, 326
Silber, J., Gledhill, T., Duchêne, G., Ménard, F. 2000, ApJ, 536, 87
Simon, M., Guilloteau, S. 1992, ApJ, 397, L47
Skrutskie, M. F., Snell, R. L., Strom, et al. 1993, ApJ, 409, 422

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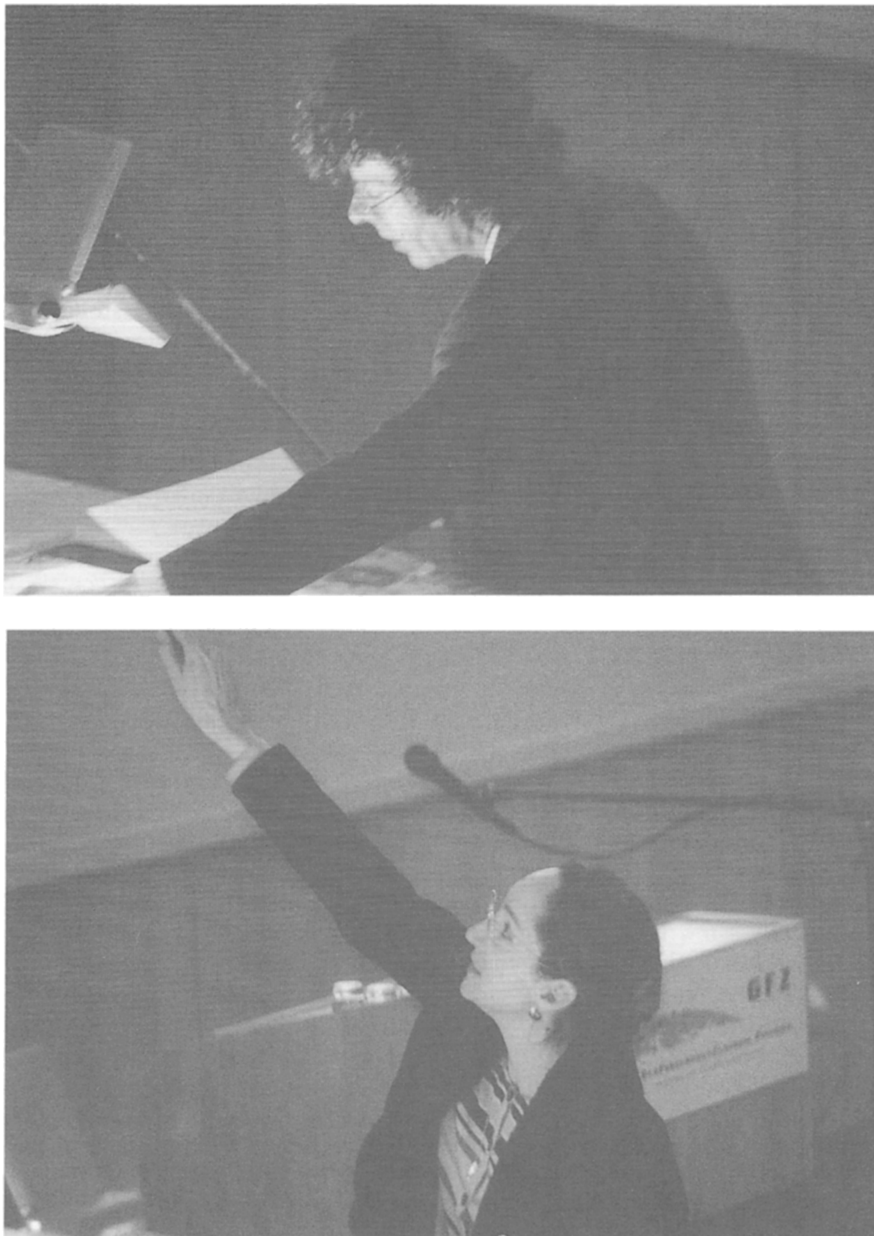

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