NEAR-INFRARED IMAGING POLARIMETRY OF THE GG TAURI CIRCUMBINARY RING

JOEL SILBER, TIM GLEDHILL, GASPARD DUCHÊNE, AND FRANÇOIS MÉNARD

Received 2000 March 2; accepted 2000 May 9; published 2000 June 12

Abstract

We present 1 μm Hubble Space Telescope/near-infrared camera and multiobject spectrometer resolved imaging polarimetry of the GG Tau circumbinary ring. We find that the ring displays east-west asymmetries in surface brightness as well as several pronounced irregularities but is smoother than suggested by ground-based adaptive optics observations. The data are consistent with a 37° system inclination and a projected rotational axis at a position angle of 7° east of north, determined from millimeter imaging. The ring is strongly polarized, up to ~50%, which is indicative of Rayleigh-like scattering from submicron dust grains. Although the polarization pattern is broadly centrosymmetric and clearly results from illumination of the ring by the central stars, departures from true centrosymmetry and the irregular flux suggest that binary illumination, scattering through unresolved circumstellar disks, and shading by these disks may all be factors influencing the observed morphology. We confirm a ~0′.25 shift between the inner edges of the near-infrared and millimeter images and find that the global morphology of the ring and the polarimetry provide strong evidence for a geometrically thick ring. A simple Monte Carlo scattering simulation is presented that reproduces these features and supports the thick-ring hypothesis. We cannot confirm filamentary streaming from the binary to the ring, also observed in the ground-based images, although it is possible that there is material inside the dynamically cleared region that might contribute to filamentary deconvolution artifacts. Finally, we find a faint fifth point source in the GG Tau field that, if it is associated with the system, is almost certainly a brown dwarf.

Subject headings: binaries: close — polarization — scattering — stars: individual (GG Tauri) — stars: pre–main-sequence

1. INTRODUCTION

GG Tau is one of the most-studied systems known to possess a tidally truncated circumbinary disk. It is a double binary, in which all four components display evidence of infrared excesses (White et al. 1999), indicating the presence of unresolved circumstellar disks. However, the most striking object in the system is the large disk of gas and dust surrounding the northern (~0′.25) binary. Since the circumbinary structure was first detected (Beckwith et al. 1990; Simon & Guilloteau 1992; Kawabe et al. 1993), many of its physical parameters have been constrained, particularly from the millimeter interferometry of Dutrey, Guilloteau, & Simon (1994) and Guilloteau, Dutrey, & Simon (1999, hereafter GDS). The disk is tidally truncated by the dynamical action of the binary at a radius of ~180 AU from the binary center of mass and extends out to at least 800 AU. From their most recent millimeter continuum and CO line flux measurements, GDS propose that 90% of the dust component of the circumbinary disk lies in a well-defined ring (inner radius ~180 AU; outer radius ~260 AU) within the extended (800 AU) disk. Their observations are consistent with an almost circular Keplerian disk, rotating about the binary’s center of mass with a projected rotational axis at a position angle (P.A.) of 7° east of north and viewed at an inclination of 37° to face-on. This implies that the northern part of the ring is closest to us (the “front”) and that the southern part of the ring corresponds to the “back.”

The first near-infrared (NIR) observations of the ring were obtained with ground-based adaptive optics by Roddier et al. (1996, hereafter RRNGJ), who published deconvolved J-, H-, and K-band images of the ring. Their data show a very clumpy ring and suggest a large degree of anisotropy in its illumination. The images also show radial filaments inside the dynamically cleared cavity, extending from the binary to the ring. At the J and K bands, the ring appears incomplete (or at least very faint) at the back. GDS found that when they registered their 1.4 mm and RRNGJ’s J-band image, there is a ~0′.25 shift of the ring’s NIR inner edge toward the binary. This could be explained if the dust ring is geometrically thick, extending to a height of ~120 AU at its tidally truncated inner radius.

In this Letter, we present the first resolved imaging polarimetry of the GG Tau system and the first space-based images of the circumbinary ring. We refer to the northern binary as “GG Tau” and follow GDS in assuming a distance of 140 AU to the Taurus star-forming region (Elias 1978).

2. OBSERVATIONS AND DATA REDUCTION

Imaging linear polarimetry data of GG Tau were obtained on 1998 April 3 with the near-infrared camera and multiobject spectrometer (NICMOS) on the Hubble Space Telescope (HST) (Proposal 7827). Camera 1 (NIC1) was used to image GG Tau through the three polaroid filters, POL0S, POL120S, and POL240S, of central wavelength 1.0459 μm (1 μm) at a pixel scale of 0′.043. The detector was operated in MULTIACCUM mode, enabling multiple nondestructive readout of the array during integration. Our data were rereduced using the STSDAS package NICPROTO to remove the “pedestal” and “shading” image anomalies (Dickinson et al. 1999). We calculated the Stokes parameters and associated errors from our data using an interactive data language (IDL) implementation of the al-

---

1 Based on observations made with the NASA/ESA Hubble Space Telescope, obtained at the Space Telescope Science Institute, which is operated by AURA, Inc., under NASA contract NAS5-26555.
2 Department of Physical Sciences, University of Hertfordshire, Hatfield, Hertfordshire AL10 9AB, England, UK.
3 Laboratoire d’Astrophysique, Observatoire de Grenoble, Université Joseph Fourier, B.P. 53, 38041 Grenoble Cedex 9, France.
4 Canada-France-Hawaii Telescope Corporation, P.O. Box 1597, Kamuela, HI 96743.
A point-spread function (PSF) subtraction or deconvolution is essential to reveal the faint circumbinary material surrounding GG Tau, since the PSF wings from the binary are highly extended and possess diffraction spikes that fill the entire frame. We have used our own observations of the DF Tau binary to subtract the GG Tau PSFs. DF Tau is the closest binary in our sample, and its ~0.1 separation is at the HST/NICMOS resolution limit. The relative flux and absolute location of the GG Tau and DF Tau components were measured with iterative PSF fitting in DAOPHOT (Stetson 1987). We then created a “double” image for each GG Tau polaroid by shifting and adding the original image to itself with the relative flux and separation of the DF Tau components. Appropriately scaled DF Tau PSFs were then subtracted from these new images. We are confident that the total flux subtracted is correct to within the photometric errors and that the PSF registration is accurate since the diffraction spikes are subtracted to almost undetectable levels away from the PSF cores.

3. RING MORPHOLOGY

A 1 μm PSF-subtracted NIC1 image of GG Tau is presented in Figure 1a. Although there are subtraction residuals in the

![Image]

**Fig. 1.** (a) NIC1 PSF-subtracted image of GG Tau at 1 μm, revealing the circumbinary ring. Subtraction residuals, most obvious in the core and inner diffraction spikes, remain as a result of the low sampling of the PSF image and errors in the relative separation and flux of the GG Tau and DF Tau binaries. The image is 56 arcsec on a side ≈800 AU assuming a distance of 140 pc to Taurus (Elias 1978) and has been scaled linearly to reveal irregularities and asymmetries. (b, c) The same data overlaid with the projected rotational axis of the ring and ellipses, based on the geometric findings of GDS, and with linear polarization vectors. These images have been rescaled to highlight the northern bright arc. (d) A simple Monte Carlo scattering simulation of the ring, overlaid with polarization vectors. The image has been convolved with the DF Tau binary to provide a like-for-like comparison with the data.
stellar cores and diffraction spikes, the ring is exceptionally well revealed. Unlike the smooth continuum flux distribution at 1.4 mm (GDS), and like RRNGJ’s J- and H-band images, the ring shows an unambiguous north-south asymmetry. A relatively thin bright arc of scattered light from the northern (front) part of the ring dominates the image with broader and fainter flux from the south (back), completing what is, essentially, an unbroken ring. The ring appears far less clumpy than in RRNGJ’s images.

The ring exhibits several examples of irregular structure: (1) the arc is brighter on its east side; (2) there is a “kink” in the ring’s south-east portion; and (3) there is a possible gap/dimming of the ring (unfortunately) at the location of the western diffraction spike. Although GDS determined the large-scale distribution of dust to be quite smooth, they used a 0.79 × 0.6 beam, and it is possible that the irregularities we may observe may be due to small-scale inhomogeneities in the ring. However, it is more likely that we are witnessing the effects of anisotropic illumination of the ring from the binary light sources and shading by the stars’ circumstellar disks. There is some evidence of scattering from clumps of dusty material inside the dynamically cleared region at the locations of both RRNGJ’s J- and H-band filamentary streamers. However, these clumps lie close to the subtraction residuals in our image and may be residuals in their own right. If real, it is possible that RRNGJ’s filaments are deconvolution artifacts caused by actual material inside the ring.

We have overlaid several ellipses onto our image in Figure 1b to help clarify the ring geometry. These have been located at the center of mass of the binary, assuming a 1 : 1 mass ratio. Ellipses 1 and 2 (green) represent circles of radii 180 AU (1.79) and 260 AU (1.86), viewed at an inclination of 37° to face-on, and should be interpreted as the projected millimeter (GDS) bounds of the ring in its equatorial plane. Ellipse 3 (cyan) marks the projected ring/cavity boundary based on GDS’s ring inclination, inner edge radius, and estimate of inner edge ring thickness (§ 1). Scattered light is clearly observed inside ellipse 1, both at the front and the back of the ring, whereas we find that ellipse 3 provides a good bound to the scattered flux edges, particularly at the front of the ring. Thus, we are able to confirm the ~0.25 displacement of the NIR front edge inward toward the binary with respect to the 180 AU inner edge derived from 1.4 mm continuum imaging. This is consistent with scattering occurring high in a geometrically thick ring, away from its equatorial plane. Further evidence for this comes from the morphology of front and backscattered flux. Figure 2 demonstrates how an optically and geometrically thick ring will produce the scattered flux morphology of the observations: the narrower flux at the front and broader flux at the back. In contrast, a geometrically thin ring would produce similar widths of scattered flux from the front and back of the ring, and an optically thin ring would produce homogeneous flux similar to GDS’s 1.4 mm continuum image. Knowledge of the ring’s orientation allows us to deduce that the thin bright arc must be caused by forward-scattering off the ring’s upper front surface and the broad fainter flux results from backscattering off the rear upper surface and ring inner edge.

Following Close et al. (1998), who reexamined the RRNGJ images, we measured the ratio of total flux received from the front and back parts of the ring. Use of RRNGJ’s “ring zone” (concentric ellipses with semimajor axes 1.25 and 1.50) and rotational axis P.A. (20° east of north) does not make sense with our image. Instead, the ratio was measured for all flux lying outside of our ring inner bound, ellipse 3. We obtain a value of 1.17 ± 0.06, which is considerably less than that measured by Close et al. (1998) from RRNGJ’s J-band image (3.6 ± 1.0). We have also measured the azimuthal intensity profile of flux contained within two (nonconcentric) ellipses, namely, ellipse 3 and an additional ellipse 0.73 larger than ellipse 3 in both semiaxes (not shown). These measurements reveal a maximum flux intensity ratio of ~4.0 between the peak of the brighter side of the arc and the back of the ring. This contrasts with the greater than 10 : 1 (2.8 mag difference) ratio obtained by RRNGJ from their deconvolved J-band data. This measurement provides an additional constraint for modeling the system.

4. RING POLARIZATION

We present in Figure 1c the first resolved linear polarization map of the GG Tau ring. At 1 μm the ring displays a broadly centrosymmetric scattering pattern that clearly indicates illumination of the ring by the central stars. A detailed interpretation of the polarization pattern will require inclusion of binary sources and, probably, the effect of the binary’s circumstellar disks. The high polarization levels observed at 1 μm, up to ~50%, are indicative of Rayleigh-like scattering from sub-micron particles. The polarization is at a minimum (~20%) in the bright arc at the front of the ring and a maximum (~50%) in the broad region at the sides and back. Using the geometry proposed by GDS, the scattering angles involved are typically ~35° at the front and ~109° (or greater) at the back (Fig. 2). Maximum polarization in the Rayleigh regime occurs when photons are scattered through right angles, and consequently, we would expect that scattering ~36° closer to maximum polarization than the front, it is more highly polarized. Thus, our polarimetry observations are entirely consistent with a thick-disk geometry (§ 1). This behavior would not be observed with a thin disk where front and backscattering angles are equally close to 90°.
5. SIMPLE MODEL

We performed some simple, single-source, Monte Carlo multiple scattering simulations to try to reproduce the ring’s major morphological and polarization features with a thick-disk geometry. We did not attempt any detailed calibration to previous determinations of disk/ring mass, but sought only to demonstrate the effects of a geometrically and optically thick ring on the scattering and polarization patterns. The ring was modeled as an arbitrary standard flared disk ($\alpha = 2$ and $\beta = 1.05$) with Gaussian-truncated inner and outer edges (parameters used by GDS). The dust density distribution parameters were all free, so there is bound to be much degeneracy between absolute density, scale height, flaring parameter $\beta$, and radial density power law $\alpha$.

Our best simulation is presented in Figure 1d and has been overlaid with its corresponding polarization vectors. Following Close et al. (1998), who implicitly modeled the ring as a flat structure, we used the Mathis & Whiffen (1989) dust grain model A with a steeper grain size power law ($p = -4.7$). However, this simulation retained the model’s original maximum grain size of 0.9 $\mu$m. The major features of the observations are all reproduced with an integrated front/back flux ratio of 1.0 and front/back maximum intensity ratio of 3.3, fitting the data well. The shift inward of the inner edge of the ring of $0\rlap{.}^\circ25$, noted by GDS, is reproduced and is roughly consistent with their ring thickness estimate at the inner edge of 120 AU at a radius of 180 AU. The global polarization features (low at the front, high elsewhere) are reproduced with polarization levels ranging from 10% to 80%, values broadly within our errors. This is another powerful endorsement of the geometrically thick disk hypothesis.

More thorough modeling of the ring will be the subject of a future paper that will consider scattering through, and shading by, the unresolved circumstellar disks, the effect of binary sources, and the choice of dust grain model, all of which will affect the scattering and polarization patterns. Finding the correct grain model is vital if the ring is to be modeled successfully, as this determines both the front/back flux ratios and the levels of polarization. Further observations of GG Tau are essential and, in particular, only multiple wavelength resolved polarimetry of the ring will provide enough constraints on the grain model to remove this as a free parameter.

6. A FIFTH ELEMENT?

We note the presence of a fifth point source in the GG Tau field that is considerably fainter than the possibly substellar (White et al. 1999) secondary of the southern binary. It is located off the field of Figure 1, 6′16 ($\approx$860 AU) from the primary of the northern binary at P.A. 242° east of north. Although the source appears in the previously published coronagraphic images of Nakajima & Golimowski (1995), these authors make no reference to it and we can find no comment regarding the object in the literature. We note that GG Tau does not lie in the densest region of the Taurus-Auriga star-forming complex, and the object may well be a background star. However, if it does lie at the same distance as GG Tau then, given its faintness, it is almost certainly a brown dwarf.

We wish to thank Dave Axon and Bill Sparks for early access to preprints and their IDL polarimetry code, Eddie Bergeron for assistance with image rereduction, John Krist for advice on the PSF subtractions, and Phil Lucas and Hiro Takami for assistance with the Monte Carlo simulations. We acknowledge use of the data analysis facilities provided by the Starlink Project, which is run by CCLRC on behalf of PPARC. An anonymous referee is thanked for useful comments.

REFERENCES

Beckwith, S. V. W., Sargent, A. I., Chini, R. S., & Güsten, R. 1990, AJ, 99, 924
Close, L. M., et al. 1998, ApJ, 499, 883
Dickinson, M., et al. 1999, NICMOS Data Handbook Version 4.0 (Baltimore: STScI)
Dutrey, A., Guilloteau, S., & Simon, M. 1994, A&A, 286, 149
Elia, J. H. 1978, ApJ, 224, 857
Guilloteau, S., Dutrey, A., & Simon, M. 1999, A&A, 348, 570 (GDS)
Hines, D. C. 1998, in ESO Conf. and Workshop Proc. 55, NICMOS and the VLT: A New Era of High Resolution Near Infrared Imaging and Spectroscopy, ed. W. Freudling & R. Hook (Garching: ESO), 63
Kawabe, R., Ishiguro, M., Omodaka, T., Kitamura, Y., & Miyama, S. M. 1993, ApJ, 404, L63
Mathis, J. S., & Whiffen, G. 1989, ApJ, 341, 808
Nakajima, T., & Golimowski, D. A. 1995, AJ, 109, 1181
Roddier, C., Roddier, F., Northcott, M. J., Graves, J. E., & Jim, K. 1996, ApJ, 463, 326 (RRNGJ)
Simon, M., & Guilloteau, S. 1992, ApJ, 397, L47
Sparks, W. B., & Axon, D. J. 1999, PASP, 111, 1298
Stetson, P. B. 1987, PASP, 99, 191
White, R. J., Ghez, A. M., Reid, I. N., & Schultz, G. 1999, ApJ, 520, 811