Apparent Motion of the Circumstellar Envelope of CQ Tau in Scattered Light

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Received 2021 March 16; revised 2021 November 1; accepted 2021 November 3; published 2021 December 22

Abstract

The study of spiral structures in protoplanetary disks is of great importance for understanding the processes in the disks, including planet formation. Bright spiral arms were detected in the disk of young star CQ Tau by Uyama et al. in the H and L bands. The spiral arms are located inside the gap in millimeter-sized dust, discovered earlier using Atacama Large Millimeter/submillimeter Array observations. To explain the gap, Ubeira Gabellini et al. proposed the existence of a planet with the semimajor axis of 20 au. We obtained multi-epoch observations of a spiral feature in the circumstellar envelope of CQ Tau in the I, band using a novel technique of differential speckle polarimetry. The observations covering a period from 2015 to 2021 allow us to estimate the pattern speed of the spiral: $-0.2 \pm 1.1$ yr$^{-1}$ (68% credible interval; positive value indicates counterclockwise rotation), assuming a face-on orientation of the disk. This speed is significantly smaller than expected for a companion-induced spiral, if the perturbing body has a semimajor axis of 20 au. We emphasize that the morphology of the spiral structure is likely to be strongly affected by shadows of a misaligned inner disk detected by Eisner et al.

Unified Astronomy Thesaurus concepts: Protoplanetary disks (1300); Polarimetry (1278); Speckle interferometry (1552)

1. Introduction

Scattered light observations of some protoplanetary disks at high angular resolution revealed spiral structures with characteristic sizes comparable to or several times larger than the solar system size (Grady et al. 1999; Muto et al. 2012; Grady et al. 2013; Benisty et al. 2015; Muro-Arena et al. 2020). Models predict the spiral waves emerge due to the influence of a companion (Juhász et al. 2015; Dong et al. 2016) or due to a gravitational instability of the disk (Dong et al. 2015). Perhaps the best tool to discriminate between those hypotheses is to measure the pattern speed of the spiral structure using observations at multiple epochs (Ren et al. 2020). In the case of a companion-induced spiral the pattern speed equals the Keplerian speed of the companion. At the same time, a gravitational instability spiral wave moves at the local Keplerian speed at all distances from the star.

Given the origin of a spiral is known, the analysis of its observational parameters can be indispensable for constraining the conditions in the disk. It can help to determine the position and mass of the companion, which is still embedded in the disk and therefore may be difficult to detect by direct techniques (Fung & Dong 2015; Zhu et al. 2015). This is especially relevant as long as the observations of exoplanets in the process of formation are still rare (see PDS70b for an exception; Kepler et al. 2018). Gravitational instability induced waves can be used to estimate the mass of the disk, one of its most important parameters (Dong et al. 2015).

The interpretation of the spiral structure observations has to take into account the effects of uneven and variable illumination caused by disk self-shadowing (Ren et al. 2020; Xie et al. 2021). These include global variations of brightness of the whole arms (e.g., MWC758; Benisty et al. 2015) or narrow shadow lanes stretching in the radial direction (e.g., HD135344B; Stolker et al. 2016), or both (e.g., HD100453; Benisty et al. 2017; Long et al. 2017). Moreover, the shadows are expected to create pressure gradients that are strong enough to induce spiral density waves, as was demonstrated by Montesinos et al. (2016). In this case their pattern speed is expected to be the same as in the case of spirals induced by a gravitational instability (Montesinos & Cuello 2018).

Bright spiral features with a characteristic projected size of 25–65 au have been recently detected in the circumstellar disk of the young stellar object CQ Tau ($\alpha = 03^h35^m58^s47, \delta = +24^\circ 44'54''.1, \ d = 149.4 \pm 1.3$ pc; Gaia Collaboration et al. 2021) in scattered polarized light (H band) and in total intensity ($L'$ band) by Uyama et al. (2020). CQ Tau is an intermediate mass HAeBe star (Spectral type: F2, age: 10 Myr, $M = 1.67 M_{\odot}$; Ubeira Gabellini et al. 2019) and a well-known UX Ori variable (Berdyugin et al. 1990) located in the Taurus star-forming region. Here, we adopt a distance of $d = 163 \pm 2$ pc from the Gaia Collaboration et al. (2018) for a consistent comparison with previous works.

A prominent depression was found in the gas and millimeter-sized dust distribution of the CQ Tau circumstellar disk by Ubeira Gabellini et al. (2019) using high angular resolution Atacama Large Millimeter/submillimeter Array (ALMA) observations in 1.3 mm continuum emission and CO lines. According to Ubeira Gabellini et al. (2019), the inclination and the position angle of the major axis of the gas disk are $35^\circ$ and $55^\circ$, respectively. The sizes of gas and large dust (1 $\mu m$–1 cm) cavities are $\approx 20$ au and $\approx 52$ au, respectively. Ubeira Gabellini et al. (2019) proposed that the cavity is cleared by a planet with a mass of $\approx 6 M_{\text{Jup}}$ and a semimajor axis of 20 au. Taking into account the mass of the star ($1.67 M_{\odot}$), the expected orbital period is 75 yr.

The existence of a planet is further supported by the spiral departures from Keplerian kinematics of the gas found by Wölfer et al. (2021). Uyama et al. (2020) reported an excess brightness of the spiral in the $L'$ band and proposed that it may be explained by additional thermal emission due to a disk–planet interaction. The possible connection between the spiral...
and the putative planet can be tested by the measurement of the spiral pattern speed; such an analysis is favored for CQ Tau by the short expected orbital period of the planet.

The spectral energy distribution of CQ Tau shows a significant near-infrared excess, which requires the presence of small dust particles in the cavity (Ubeira Gabellini et al. 2019). The inner disk with a typical size of 0.45 au around the star was detected in the $K$ band using the Palomar Testbed Interferometer (Eisner et al. 2004). These facts and UX Ori variability indicate that the inner part of the circumstellar disk may affect the illumination conditions of the outer disk, which should be taken into account during analysis.

In the current paper, we present observations of the circumstellar envelope of CQ Tau using differential speckle polarimetry (DSP) at 48 epochs distributed over the period of more than 5 yr in the $I_c$ band (effective wavelength 0.806 μm). DSP is a novel technique based on the analysis of series of short-exposure frames obtained through a dual-beam polarimeter without an adaptive optics correction. The spiral structure with a characteristic size of 0″1–0″15, which corresponds to 15–25 au at the distance of the source, was detected in the majority of cases; our observations allow us to trace the evolution of its morphology. The work is organized as follows. Sections 2 and 3 contain the description of the observational data and processing methods, respectively. In the Section 4, we compare our data with those available in the literature and investigate the variability of the morphology of the spiral structure of CQ Tau. The conclusions are given in Section 5.

2. Observations

The observations were made using the SPeckle Polarimeter (SPP), which is a dual-beam polarimeter and speckle camera equipped with an Electron Multiplying CCD (EMCCD) sensor, Andor iXon 897. The instrument is installed at the 2.5 m telescope of the Caucasian Mountain Observatory of the Sternberg Astronomical Institute of Lomonosov Moscow State University (Kornilov et al. 2014). Splitting of the orthogonally polarized beams is done by a Wollaston prism, and both images formed by the latter are located side by side on the same detector; see Figure 2. The instrument includes a rotating half-wave plate (HWP) for the modulation of the polarization state of incoming radiation. Atmospheric dispersion is compensated for by a dedicated unit consisting of two rotatable direct vision Amici prisms. The plate scale of the instrument is 0″0206 pix$^{-1}$. The plate scale determination and calibration of the position angle of the instrument is performed by observations of wide binaries, as described by Safonov et al. (2017). The field of view of the instrument is a rectangle with the dimensions of 5″ × 10″.

The SPP can operate in several bands of the visible wavelength range, although in the present work we use observations in the $I_c$ band only, at an effective wavelength $\lambda = 806$ nm. At wavelengths longer than 460 nm, including the whole $I_c$ band, the detector oversamples the diffraction-limited point-spread function of the feeding telescope, which has an aperture diameter $D = 2.5$ m. The main detector of the SPP has a negligible effective readout noise, smaller than 0.1 e$^-$, and can run at high frame rates very close to a 100% duty cycle thanks to the frame transfer technology. These features of the SPP, and other EMCCD-based speckle interferometers in general, ensure the reliable detection of the speckle structure of the images degraded by atmospheric optical turbulence, which subsequently allows the computation of the Fourier spectra of these images. In our case the resulting Fourier transforms are used as an input for the DSP algorithm. The detailed description of the instrument design and calibration procedures is presented by Safonov et al. (2017), who also discuss the implementation of the speckle interferometry and integral polarimetry with the SPP.

The observations for the present study were obtained in so-called fast polarimetry mode. In this mode the detector obtains a series of short-exposure images at 33 frames per second, which gives an exposure time of 30 ms for a single frame. At the same time the HWP continuously rotates at 300° s$^{-1}$. The rotation of the HWP serves two purposes. First, it allows for the measurement of both Stokes parameters corresponding to linear polarization. Second, it switches the images corresponding to orthogonal polarizations in the beams of the polarimeter every five frames, allowing for the application of the double difference technique (Bagnulo et al. 2009). The double difference discards most of the instrumental effects associated with the differences between the two channels of the polarimeter.

In total, we obtained 48 series of CQ Tau in the period from 2015 October 29 to 2021 February 2, all of them in the $I_c$ band; they are listed in Table 1. The series duration varied from 2000 to 60,000 frames (11,000–12,000 frames in most cases). The integral total flux polarimetry extracted from these observations is presented in Figure 1 and Table 1. Some observations were secured while the instrument was installed at the Cassegrain focus, and some at the Nasmyth focus, as indicated in the observational log, Table 1. For the observations at the Nasmyth focus the polarimetric measurements were corrected for the instrumental polarization by the application of the inverse Mueller matrix of the telescope; see details in Safonov et al. (2017). In some cases we estimated the magnitude by quasi-simultaneous observations of the standard star HIP25001.

3. Processing

3.1. Differential Polarimetric Visibility Estimation

All observations were processed by the DSP method. For each frame, processing started with the subtraction of the bias and background. Then the images $F_L$ and $F_R$ corresponding to the beams of the polarimeter were extracted and their Fourier transforms $\tilde{F}_{L,i}(f)$ and $\tilde{F}_{R,i}(f)$ were computed. Here, $L$ and $R$ indices mean the left and right beam of the polarimeter. Subscript $i$ is the frame number in series, and $f$ is the vector of spatial frequency. The distortion of the Wollaston prism and the atmospheric dispersion compensator prisms was corrected in Fourier space. These steps are illustrated in Figure 2.

The resulting spectra were combined in the following way (we omit the dependence on spatial frequency $f$ for brevity):

$$R_{ch} = 1 + \frac{\langle (\tilde{F}_{L,i} - \tilde{F}_{R,i})(\tilde{F}_{L,i} + \tilde{F}_{R,i})^\ast \cos(\theta / \lambda) \rangle_i}{\langle (\tilde{F}_{L,i} + \tilde{F}_{R,i})(\tilde{F}_{L,i} + \tilde{F}_{R,i})^\ast \rangle_i} \equiv R^\ast_{ch},$$

$$R_{ch} = 1 + \frac{\langle (\tilde{F}_{L,i} - \tilde{F}_{R,i})(\tilde{F}_{L,i} + \tilde{F}_{R,i})^\ast \sin(\theta / \lambda) \rangle_i}{\langle (\tilde{F}_{L,i} + \tilde{F}_{R,i})(\tilde{F}_{L,i} + \tilde{F}_{R,i})^\ast \rangle_i} \equiv R^\ast_{ch}.$$  

2

Here, $\theta$ is the position angle of the HWP for the frame $i$. Superscript $\ast$ stands for the complex conjugation. The parentheses $\langle \rangle_i$ indicate averaging over frames in series. These equations represent the demodulation of the signal, initially
modulated by rotation of the HWP. They decompose the signal into harmonics $h$. As long as the detector obtained $\approx 40$ frames per revolution of the HWP, we calculated values (1) and (2) up to $N_h = 20$. $N_e$ is the average number of photons in a single frame.

The general idea of Equations (1)–(2) is to average the cross-spectra of images corresponding to Stokes $Q$ and $I$ and subsequently normalize them by the average power spectrum of the Stokes $I$ image. Previously in Safonov et al. (2019; hereafter S19), we demonstrated that $R_{ch}$ and $R_{sh}$ corresponding to $h = 4$ can be considered as estimators of differential polarimetric visibility (DPV) $R_Q$ and $R_U$:

$$R_{ch}(f) = R_{Q,ins}(f)R_Q(f),$$

$$R_{sh}(f) = R_{U,ins}(f)R_U(f).$$

$R_{ch}$ and $R_{sh}$ for $h = 0$ characterize the optics after the HWP. Other harmonics ($h \neq 0$ and $h = 4$) are expected to be zero and thus can be used for the noise estimation (S19, Appendix B). The factors $R_{Q,ins}(f)$ and $R_{U,ins}(f)$ characterize the effect of instrumental polarization; they are discussed below.

The DPV is defined by equations:

$$R_Q(f) = \frac{\tilde{I}(f) + \tilde{Q}(f)}{\tilde{I}(f) - \tilde{Q}(f)}, \quad R_U(f) = \frac{\tilde{I}(f) + \tilde{U}(f)}{\tilde{I}(f) - \tilde{U}(f)}.$$  

Here, $\tilde{I}$, $\tilde{Q}$, $\tilde{U}$ are the Fourier transforms of the Stokes parameter distributions in the object. One can see that the DPV is the ratio of visibilities of the object in orthogonal polarizations and can be defined for two Stokes parameters describing linear polarizations $Q$ and $U$.

The measurement of the modulus of $R_Q$ and $R_U$ was demonstrated by Norris et al. (2012) using adaptive optics assisted aperture masking with NaCo on the Very Large Telescope. Unlike that experiment, in SPP the full pupil of the 2.5 m telescope is employed, which provides a larger throughput of the system. Apart from this, no adaptive optics correction is used in our case. The signal in the Fourier spectrum of the image at high frequencies is lower than it would be with such a correction. However, the optical system is simpler and more suitable for precision polarimetry. Note that DSP allows one to obtain not only the modulus but also the argument of $R_Q$ and $R_U$.

The quantities in Equations (1)–(5) are defined in the instrument reference system. The formulae for their conversion to horizontal and equatorial reference frames are given in S19, Appendix B. The correction for instrumental terms $R_{Q,ins}$ and $R_{U,ins}$ is done in the horizontal reference frame, as long as these factors are associated with the telescope, which has an altazimuth mount. This operation is described in Appendix B. Then, $R_Q$ and $R_U$ are converted to the equatorial reference frame. For observations secured at the Cassegrain focus the instrumental terms $R_{Q,ins}$ and $R_{U,ins}$ are within $10^{-4}$ of unity, much smaller than the typical level of signal for CQ Tau. Therefore, the correction for the instrumental polarization effect was not applied for this focus.

As an example of the measurement of $R_Q$ and $R_U$, we provide the data for CQ Tau obtained at the Cassegrain focus at UT 2015 October 29 00:51 in Figure 3. Here, the DPV can be traced to frequencies $0.7–0.8f_c$, where $f_c$ is the cutoff frequency $D/\lambda$. $D = 2.5$ m is the telescope aperture diameter and $\lambda = 0.806 \mu m$ is the wavelength of the observation. Hence the cutoff frequency $f_c = 3.1 \times 10^9$ RAD$^{-1}$ in our case.

In order to characterize the quality of the data, we estimated the noise of $R_Q$ and $R_U$ using the method presented in S19. Then, we averaged the noise in an annular region of Fourier space limited by $0.3f_c < |f| < 0.4f_c$. For the series obtained at 2015 October 29 00:51 for CQ Tau it is $6.5 \times 10^{-3}$ RAD, in terms of the rms. This quantity computed for all series is presented in the seventh column of Table 1.

Figure 3 also contains a measurement for the unpolarized star HIP38325 secured at UT 2015 October 30 02:40 and the polarization standard star HD19820 secured at UT 2019 December 12 20:16. In both cases the $I$ band was used. Both stars have no circumstellar dusty envelopes.

One can see that $R_Q$ and $R_U$ for CQ Tau significantly deviate from the constant level. This behavior is different from that of the unpolarized star and the polarization standard star.
3.2. Reconstruction of the Image of the Envelope in Polarized Intensity

If the object can be represented as a sum of a point-like star and an extended envelope, the Fourier transforms of Stokes parameter distributions will have the following form:

\[ \tilde{I}(f) = \bar{I} + \tilde{I}_s(f), \]
\[ \tilde{Q}(f) = q \bar{I} + \tilde{Q}_s(f), \]
\[ \tilde{U}(f) = u \bar{I} + \tilde{U}_s(f). \]

Here, \( \bar{I} \) is the Fourier transform of the image of the star, a value equal to the flux from the star \( I \) for all frequencies. The terms \( q \) and \( u \) are the dimensionless Stokes parameter of the star, and \( \tilde{I}_s(f), \tilde{Q}_s(f), \) and \( \tilde{U}_s(f) \) are Fourier transforms of the envelope image in Stokes parameters \( I, Q, \) and \( U \), respectively.

In the following we take into account the fact that the polarization of the star is small, \( q_s \ll 1, u_s \ll 1 \), and the envelope is faint compared to the star, \( \tilde{Q}_s \ll \tilde{I}_s, \tilde{U}_s \ll \tilde{I}_s \). Substituting (6)-(8) into (5) and keeping only first-order terms, we obtain for the Fourier transforms of the envelope flux distributions:

\[ \tilde{Q}_s(f) = 0.5(\mathcal{R}_Q(f) - 1), \]
\[ \tilde{U}_s(f) = 0.5(\mathcal{R}_U(f) - 1). \]

Here, the quantities on the left side of the equations are normalized by the total stellar flux and additionally include the contribution of polarized direct stellar radiation:

\[ \tilde{Q}_s(f) = (\tilde{Q}_s(f)/I_s) + q_s, \tilde{U}_s(f) = (\tilde{U}_s(f)/I_s) + u_s. \]

As one can see from Figure 3, \( R_Q \) and \( R_U \) and subsequently \( \tilde{Q}_s(f) \) and \( \tilde{U}_s(f) \) have an acceptable signal-to-noise ratio up to frequencies 0.7-0.8\( f_s \). Therefore, we multiplied them by a low-pass filter in order to suppress the wings of the point-spread function in the image space and reduce the effect of the noise. For this spatial filter we used the optical transfer function of a circular aperture:

\[ G(f) = (2/\pi)\arccos(z\sqrt{1-z^2}), \]

where \( z = 2|f|\lambda/D' \). We took \( D' = 0.7D \), where \( D = 2.5 \) m for all of the data.

\( \tilde{Q}_s(f) G(f) \) and \( \tilde{U}_s(f) G(f) \) are defined in the region \( |f_x| < f_x/2, |f_y| < f_y/2 \) in Fourier space. Here, \( f_x = 1/\alpha_x \) is the sampling frequency, and \( \alpha_x \) is the angular scale of the detector. Therefore the image produced by applying an inverse Fourier transform to them will have the pixel size of \( \alpha_x \). We artificially increased the region in which \( \tilde{Q}_s(f) G(f) \) and \( \tilde{U}_s(f) G(f) \) are defined two times by padding it with zeros. This operation did not add or remove any information from the data; however, the pixel size in the resulting image decreased to \( \alpha_x/2 \), making the appearance of the object in the image space smoother.

Filtered and padded \( \tilde{Q}_s(f) \) and \( \tilde{U}_s(f) \) were transformed into the image space by applying an inverse FFT. This reconstruction process results in the estimation of the polarized intensity in the circumstellar environment \( Q'(\alpha) \) and \( U'(\alpha) \), where \( \alpha \) is a two-dimensional vector of the spatial coordinate relative to the point-like unpolarized star. The quantities \( Q'(\alpha) \) and \( U'(\alpha) \) are then used for the computation of the polarized intensity \( I_p(\alpha) \) and the angle of polarization \( \chi(\alpha) \):

\[ I_p(\alpha) = \sqrt{Q'^2(\alpha) + U'^2(\alpha)}, \]
\[ \chi(\alpha) = \frac{1}{2}\arctg(U'(\alpha)/Q'(\alpha)). \]

Recall that the polarized intensity is the product of the total intensity and the fraction of polarization.

The examples of \( I_p(\alpha) \) and \( \chi(\alpha) \) are presented in Figure 3 in the rightmost column. As long as the spatial filter is nonzero up to frequencies 0.7\( f_s \equiv 2.17 \times 10^6 \) RAD\(^{-1}\), the reconstructed image of the circumstellar envelope has a typical resolution of \( \approx 0.1' \). For the unpolarized star HIP38325, the image does not contain any significant structure. By contrast, in the image of the CQ Tau envelope, a spiral arm 0.012 to the north from the star is present. There is also a less prominent feature \( \lesssim 0.1' \) to
the south of the star. Both features demonstrate an azimuthal polarization pattern that indicates that they are part of a reflection nebula associated with the star.

Note that the estimations $Q'\alpha$ and $U'\alpha$ contain the contribution from the polarized direct radiation of the star. This effect is prominent in the case of the polarization standard HD19820. In the bottom right panel of Figure 3 one can see a bright source of polarized radiation coincident with the star. In case of CQ Tau there is such a source as well, which is discussed in Section 4.2.

### 4. Results

#### 4.1. Comparison with Data from the Literature

The fact that the northern spiral is brighter and farther from the star than the southern one suggests that it lies on the far edge of the flared disk, which has more favorable conditions for scattering the stellar radiation. This assumption is supported by the kinematics data of Wölfer et al. (2021), which show that the disk rotates counterclockwise and the northwest edge is farther away.

Two spiral arms were detected in the disk of CQ Tau earlier by Uyama et al. (2020) in the $H$ band using Subaru/HiCIAO. The approximation of the spiral arms from their work is compared to our image in Figure 4. As one can see, the brighter spiral found by Uyama et al. (2020) is slightly more distant from the star and at approximately the same position angle as in our images. The larger distance from the star is probably explained by the longer wavelength in the case of the HiCIAO observations: 1.6 $\mu$m. Indeed, at the wavelength of our observation, 0.8 $\mu$m, the optical depth rises faster along the line of sight connecting the surface of the disk and the star. Thus one can expect that the region that predominantly scatters the light is closer to the star. The fainter arm from Uyama et al. (2020) at 0.3 from the star turned out to be inaccessible to us. DSP is less sensitive to fainter outer envelopes than adaptive optics assisted coronagraphs like HiCIAO due to the less efficient separation of the radiation of a bright central source and faint circumstellar material.

The comparison with ALMA data in 1.3 mm continuum emission from Ubeira Gabellini et al. (2019) is presented in the same Figure 4. In millimeter waves, the envelope appears as a
relatively large ring. The structures found by Uyama et al. (2020) and in the present work are located inside this ring. Presumably the spiral in scattered light lies on the inner side of a dust torus facing the star. We note that ALMA traces millimeter-sized dust particles, while visible and near-infrared radiation is scattered by much smaller particles. Spirals in scattered light inside a millimeter-wave dust ring was reported for EM’ SR 21 by Muro-Arena et al. (2020).

Palomar Testbed Interferometer observations of Eisner et al. (2004) in the K band demonstrated the existence of an inner disk around CQ Tau with the characteristic size of 2.7 mas (Gaussian fit), which corresponds to 0.45 au at the distance of the source. The major axis of the inner disk has P.A. = 104° ± 6°, and the inclination of the disk is 48° ± 5°. The disk with these parameters is indicated in Figure 4 by the red line. One can see that the orientations of the inner disk and the larger disk found by millimeter-wave observations are very different.

If the inner disk is geometrically thick, its inclination can be even larger. The fact that CQ Tau is a UX Ori variable (Berdyugin et al. 1990; Natta et al. 2000; Shakhovskoj et al. 2005) favors a larger inclination; the variable stars of this type display irregular brightness minima induced by passages of dust clouds across the line of sight (Grinin 1988). The minima are accompanied by the rise of polarization. The UX Ori variability is typical for young stellar objects with highly inclined disks. On the basis of high-resolution ESPaDOnS spectra, Dodin & Suslina (2021) found recently that the clouds that occasionally eclipse CQ Tau have structures comparable in size with the stellar diameter.

4.2. Is the Spiral Induced by a Planet?

The pattern speed of a spiral induced by a planet is defined by the orbital motion of that planet. Therefore if the spiral detected by Uyama et al. (2020) and confirmed by our observations is indeed induced by the planet proposed by Ubeira Gabellini et al. (2019), its pattern speed should be ≈4.8 yr⁻¹, which corresponds to an orbital period of 75 yr. The direction of motion should be counterclockwise.

To test this hypothesis we considered the following model of object variability. First, as long as CQ Tau is a UX Ori variable, we allowed for a change in the brightness and total polarization of an unresolved source. Second, we assumed that the envelope can rotate as a whole. For rotation modeling, we did not deproject the disk because, according to Ubeira Gabellini et al. (2019), its inclination is not so large: 35° (Dong et al. 2016).

Using these assumptions we approximated each individual measurement of the DPV with a reference one. For the reference observation we took the data obtained at UT 2018 November 25 23:49, which have a relatively low noise level and lie roughly in the middle of the considered time period. Note that this approximation employs the DPV measurements directly, not the images reconstructed using the method from Section 3.2. The approximation details are discussed in Appendix C. In Appendix D we study the influence of the choice of the reference observation on the result.

For each observation we obtained a set of parameters ω, η, ω', η', ζ, and η by minimization of the χ² statistic. The first two of these parameters characterize the change in total polarization of the unresolved source, and the third defines the change in its brightness. We are interested most in parameter ω, which is the rotation angle between the reference observation and a given one. The estimations of η are presented in Figure 5 as a function of time.

In the same figure, the weighted linear approximation by η = η₀ + ωt is presented. Values of η exhibit a significant spread, which is probably due to variable shadowing of the envelope. However, the overall trend is absent. The parameters of the linear fit are: η₀ = −0.4 ± 1.6 and ω = −0.2 ± 1.1 yr⁻¹ (68% credible intervals). Recall that the pattern speed expected for a planet-induced spiral is ωₚ = 4.8 yr⁻¹ (counterclockwise direction); the corresponding trend is indicated by the red line in figure. Therefore, we reject the hypothesis that the spiral in the scattered light detected in our study is caused by a planet with an orbital period of 75 yr at the level of 4.3σ.

4.3. The Spiral as an Effect of Shadowing by the Inner Disk

The increased optical depth for the lines of sight passing near the equator of the inner disk should produce shadows on the outer disk. Such a mechanism was proposed to explain the appearance of disks in scattered light for a number of objects: HD100453 (Benisty et al. 2017), DoAr 44 (Casassus et al. 2018), and RXJ1604.3-2130 (Pinilla et al. 2018). Given the small inclination of the outer disk, the shadow position should roughly coincide with the line of intersection of the inner and outer disk equator planes.

In our case, the brighter northern spiral arm indicates that the northern edge of the inner disk is farther from us. Taking into account the inclinations and position angles of the disks, the expected position angles of the shadow are 140° and 320°, as indicated in Figure 4. The mutual configuration of the disks is illustrated in Figure 6. The angle between the axes of rotation of the inner and outer disks is 40°. The orientations of the...
shadows match the positions of the gaps in the spiral structure. Therefore, the spirals detected by Uyama et al. (2020) and in the present work may be actually rings with shadows cast by the inner disk, rather than physical structures in seen scattering dust.

5. Conclusions

The structures found in protoplanetary disks in scattered light show variability on timescales from days to years. Both physical motion (Ren et al. 2018, 2020) and illumination changes (Stolker et al. 2016; Benisty et al. 2017; Casassus et al. 2018; Pinilla et al. 2018) are observed. In each specific case it is important to differentiate between these two basic explanations. The analysis of variations in the morphology of envelopes is greatly facilitated by multi-epoch observations made by a homogeneous technique.

In the current paper, we present observations of the circumstellar envelope of a young star CQ Tau by differential speckle polarimetry in the L-band at the 2.5 m telescope of the Caucasian Mountain Observatory of Lomonosov Moscow State University, covering the period from 2015 to 2021. We detect a spiral arm at the characteristic distances 0°1−0°15 north of the star. The structure is located at the same position angle as the spiral arm discovered previously by Uyama et al. (2020) at a slightly larger stellocentric distance. We also report the presence of a southern, closer to the star, arm of the spiral.

To explain the large gap in the gaseous and dust disk of CQ Tau, Ubeira Gabellini et al. (2019) proposed the existence of a planet on an orbit with a semimajor axis of 20 au. This possible planet could potentially generate structures appearing as spiral arms in scattered light, as was proposed for SAO 206462 (Xie et al. 2021), MWC 758 (Ren et al. 2018), and AB Aur (Boccaletti et al. 2020). The pattern speed of the respective spiral in this case is dictated by the orbital motion of the planet: 4°8 yr−1. On the basis of observations covering a period of more than 5 yr, we estimated the spiral pattern speed of CQ Tau to be −0°2 ± 1°1 yr−1 (68% confidence interval). We conclude that the spiral in scattered light is not caused by that planet. However, it is not excluded that the spiral is generated by a planet farther away from the star, at distances of ≳40−50 au.

The relative stability of the spiral structure may indicate that its morphology is largely determined by shadowing of the outer disk by the misaligned inner one, as in the cases of HD100453 (Benisty et al. 2017), DoAr 44 (Casassus et al. 2018), and RXJ1604.3-2130 (Pinilla et al. 2018). The gaps in the spiral structure seen in scattered light at position angles ≈160° and ≈340° correspond to the expected positions of the shadows from the inner disk found earlier by Eisner et al. (2004). A slow precession of the inner disk is still possible. In future analyses and interpretations of the spiral structure of CQ Tau, it is important to consider the possibility that it is not uniformly illuminated.

We are grateful to Sergei Lamzin for the useful comments on the manuscript. Constructive comments by the anonymous referee allowed us to improve the analysis and presentation. We acknowledge the financial support of the Russian Science Foundation Public Monitoring Committee 20-72-10011. Scientific equipment used in this study was bought partially by the funds of the M. V. Lomonosov Moscow State University Program of Development.

Appendix A

Observations of CQ Tau

The observations of CQ Tau used in current work are presented in Table 1.
Appendix B

Correction of Instrumental Polarization

The instrumental polarization induced by a mirror can be modeled using the formalism of Stokes vectors and Mueller matrices. The Stokes vector of outgoing radiation is the product of the Stokes vector of incoming radiation and the Mueller matrix of the mirror. For the integral polarimetry, the Mueller matrix of the mirror is averaged over the beam. Thus, mirrors acting in a symmetrical configuration, e.g., the primary and the secondary, do not modify the polarization of incoming radiation except for a negligible depolarization. When the SPP is mounted at the Nasmyth focus the whole system up to
and proposes the instrumental polarization standard. The date of the respective observation is indicated in the title.

Here, the instrumental polarization becomes quite substantial. It varies from 2% to 4% over the wavelength range of the SPP. In this respect it differs from the azimuthal polarization pattern, as in the case of CQ Tau, which is a genuine feature of a scattering reflection nebula.

### Table 2

| Parameter Polarization Parameters in the $I$ Band at the Nasmyth Focus |
|-----------------------------|-----------------------------|
| Parameter (1)              | Value (2)                   |
| $q_{ins}$, %                | 3.44 ± 0.10                 |
| $u_{ins}$, %                | 0 ± 10                      |
| $s_{q ins}$, μas            | 67 ± 29                     |
| $k_{q ins}$, μas            | 702 ± 65                    |
| $s_{u ins}$, μas            | −344 ± 19                   |
| $k_{u ins}$, μas            | 37 ± 18                     |

Note. See the text for the definition of the symbols.

beam splitter possesses axial symmetry, thus ensuring a low level of the instrumental polarization. Measurements of unpolarized stars demonstrated the instrumental polarization is lower than $10^{-4}$ (Safonov et al. 2017).

At the Nasmyth focus an oblique reflection by the diagonal M3 mirror is added, axial symmetry is broken, and the instrumental polarization becomes quite substantial. It varies from 2% to 4% over the wavelength range of the SPP. In Safonov et al. (2017) we constructed a model of the instrumental polarization induced by the M3 mirror of the 2.5 m telescope and provided a method for its correction.

While the instrumental polarization is definitely important for measuring the integral polarization, for diffraction-limited imaging it adds a new level of complexity. The fact that the reflection geometry is different for different points in the pupil lead to the emergence of so-called differential polarization aberrations (Breckinridge et al. 2015). The first-order term of these aberrations manifests itself as a phase ramp in $R_{Q,ins}$ and $R_{U,ins}$ (S19). S19 contains an extensive analysis of instrumental terms $R_{Q,ins}$ and $R_{U,ins}$ and proposes the following model for them:

$$R_{Q,ins} = 1 + 2q_{ins} + i4\pi (s_{q ins}^* f_x + t_{q ins}^* f_y),$$

(A1)

$$R_{U,ins} = 1 + 2u_{ins} + i4\pi (s_{u ins}^* f_x + t_{u ins}^* f_y).$$

(A2)

Here, $f_x$ and $f_y$ are the components of the two-dimensional frequency vector. Terms $q_{ins}$ and $u_{ins}$ are the polarization of an intrinsically unpolarized star detected by the instrument. Terms $s_{q ins}^*$, $t_{q ins}^*$, $s_{u ins}^*$, and $t_{u ins}^*$ are the components of the so-called instrumental polarimetric signal (IPS). Equations (A1) and (A2) assume that $R_{Q,ins}$, $R_{U,ins}$ are defined in the horizontal reference system.

The quantities $q_{ins}$, $u_{ins}$, $s_{q ins}$, $t_{q ins}$, $s_{u ins}$, and $t_{u ins}$ were determined in S19 from measurements of point-like unpolarized stars; see their values for the $I$ band in Table 2. At the Nasmyth focus the IPS is large and should be corrected through the division of observed $R_{Q,4}$ and $R_{U,4}$ by (A1) and (A2), respectively. This operation is performed in the horizontal reference system.

Figure 7 demonstrates the same quantities as in the fifth column of Figure 3, but obtained at the Nasmyth focus and corrected for the instrumental polarization. Again for comparison we give the observations for a point-like unpolarized star and a point-like polarization standard, HIP8370 and HD25443, respectively. One can see that the spiral feature is persistent for CQ Tau. It is not observed for either the unpolarized star or the polarization standard.

The image of the polarization standard HD25443 exhibits a ring in polarized light, which corresponds to the first bright ring of the Airy function. Note that this ring has a constant polarization angle equal to the integral polarization angle of the star. In this respect it differs from the azimuthal polarization pattern, as in the case of CQ Tau, which is a genuine feature of a scattering reflection nebula.

### Appendix C

**Approximation of One Observation by Another**

Section 4.2 is based on the approximation of a given observation $k$ by a reference one $j$. The differential polarization visibility for the reference observation can be written as:

$$R_{Q,j}(f) = 1 + 2q_j + 2I_j^{-1}Q_{c,j}(f).$$

(B1)

according to Equations (6)–(7). Recall that $q_c$ is the polarization of the star, $Q_c$ is the Fourier transform of the envelope image in Stokes parameter $Q$, and $I_*$ is the stellar flux. If the envelope is rotated by $\eta$ (positive for counterclockwise rotation), then the DPV will be:

$$R_{Q,j}(\eta; f) = 1 + 2q_c + 2I_*^{-1}Q_{c,\eta}(\eta; f).$$

(B2)

The rotated version of $\tilde{Q}_{c,\eta}$ will depend on both $\tilde{Q}_c$ and $\tilde{U}_c$ due to transformation of the Stokes parameters in the rotated reference system. For the equations describing the rotation of $R_Q$ and $R_U$, see Appendix B of S19.
Suppose that the stellar flux increases by $\zeta$ and stellar polarization changes to $q_\ast'$. The DPV will change in the following way:

$$R_{Q,j}^k(\eta;f) = 1 + 2q_\ast' + 2(d_\ast)^{-1}Q_{c,j}(\eta;f).$$

(B3)

Expressing $Q_{c}$ from (B2) and substituting it in (B3), we obtain the formula describing the transformation of the measurement:

$$R_{Q,j}^k(\eta;f) = 1 + 2[q_\ast' - \zeta^{-1}q_{\ast}] + \zeta^{-1}[R_{Q,j}^k(\eta;f) - 1].$$

(B4)

A similar relation can be formulated for Stokes $U$:

$$R_{U,j}^k(\eta;f) = 1 + 2[u_\ast' - \zeta^{-1}u_{\ast}] + \zeta^{-1}[R_{U,j}^k(\eta;f) - 1].$$

(B5)

The second terms in these equations will be considered as new parameters: $q_\ast'' = q_\ast' - \zeta^{-1}q_{\ast}$ and $u_\ast'' = u_\ast' - \zeta^{-1}u_{\ast}$.

The comparison of measurements is performed by the computation of the residual of the following form:

$$\mathcal{M}(f) = \mathcal{L}_Q(f) + \mathcal{L}_U(f),$$

(B6)

where

$$\mathcal{L}_Q(f) = \frac{R_{Q,j}^k(f) - R_{Q,j}^k(f)}{\sqrt{\sigma_{R_{Q,j}^k}(f) + \sigma_{R_{Q,j}^k}^2(f)}},$$

$$\mathcal{L}_U(f) = \frac{R_{U,j}^k(f) - R_{U,j}^k(f)}{\sqrt{\sigma_{R_{U,j}^k}(f) + \sigma_{R_{U,j}^k}^2(f)}}.$$  

(B7)

Here, $R_{Q,j}^k$ and $R_{U,j}^k$ are the DPV measurements for the observation $k$, and $R_{Q,j}^*\ast$ and $R_{U,j}^*\ast$ are the same, but for observation $j$, modified according to Equations (B4) and (B5). Terms $\sigma_{R_{Q,j}^k}$ and $\sigma_{R_{U,j}^k}$ are the errors of estimation of the DPV; the method of their determination can be found in Appendix B of S19.

For each observation we determine four parameters: $q_\ast''$, $u_\ast''$, $\zeta$, and $\eta$ by minimization of the total residual:

$$\sum_{|f| < 0.3f_c} \mathcal{M}(f).$$

(B8)

Here, the summation takes place for frequencies smaller than 0.7$f_c$, where $f_c$ is the cutoff frequency. Note that the total residual defined by (B8) is technically a $\chi^2$ statistic. The posterior probability of parameters was sampled using the affine-invariant ensemble Markov Chain Monte Carlo method (Goodman & Weare 2010). Fifty walkers and $2 \times 10^4$ iterations in total were used.

An example of the resulting posterior for observation UT 2019 October 26 22:10 approximated by UT 2018 November 25 23:49 is displayed in the left part of Figure 8. The best values for the parameters are: $q_\ast'' = -0.06% \pm 0.07%$, $u_\ast'' = -1.32% \pm 0.07%$, $\zeta = 0.67 \pm 0.05$, and $\eta = 8.8 \pm 2.7$ (values after the $\pm$ sign are 68% confidence intervals). The components of the corresponding residual (B7) are presented in the right part of Figure 8. The absence of significant departures indicates that the fitting of one observation by modified version of another is of satisfactory quality.
Figure 9. Left panel: comparison of rotation angles $\eta$ for individual observations with respect to two reference observations. Along the horizontal axis is $\eta_1$ evaluated relative to an observation at UT 2021 November 25; along the vertical axis is $\eta_2$ evaluated relative to an observation at UT 2020 October 14 (see Section 4.2 and Appendix B for details of approximation). Right panel: solid line—cumulative distribution function of differences $\eta_1 - \eta_2$, normalized by the uncertainties. Dashed line—normal distribution with variance equal to unity and mean equal to $-0.4$; see the text for the discussion.

Appendix D
The Dependence of Results on Reference Observation Selection

In Section 4.2 all observations were compared to a reference one in order to search for the rotation of the envelope. Here, we consider how the choice of the reference observation may affect the results of this analysis. For an alternative reference observation we took the data obtained on UT 2020 October 14 23:00. Then, the procedure described in Section 4.2 was repeated for this reference.

The resulting rotation angles $\eta_1$ and $\eta_2$ for two references are directly compared in the left panel of the Figure 9. The cumulative distribution function of $\eta_1 - \eta_2$, normalized by its uncertainty is presented in the right panel of the same figure. These normalized deviations are expected to follow a shifted standard normal distribution. The shift emerges because the envelope may have rotated between moments 2018 November 25 23:49 and 2020 October 14 23:00. One can see that the distribution of deviations indeed follows the normal distribution for the majority of data points. However, the wings of the distribution are larger than expected.

The dependence of rotation angles $\eta$, determined using the alternative reference observation, on time were fit with a linear law, as it was done in Section 4.2. The parameters of the fit are $\eta_0 = 1.74 \pm 1.7$ and $\omega = -0.07 \pm 0.09 \text{ yr}^{-1}$ (68% credible intervals). They coincide within errors with the values obtained using the observation for UT 2018 November 25 23:49 as a reference. We conclude that the choice of the reference observation has no major effect on the results of Section 4.2.

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