THE INNER ENVELOPE AND DISK OF L1527 REVEALED: GEMINI L'-BAND-SCATTERED LIGHT IMAGING

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ABSTRACT

We present high-resolution L'-band imaging of the inner scattered light structure of Class 0 protostar L1527 IRS (IRAS 04368+2557) taken with the Gemini North telescope. The central point-source-like feature seen in Spitzer Space Telescope IRAC images is resolved in the Gemini image into a compact bipolar structure with a narrow dark lane in the center. Two scattered light lobes are extended \(~1''8\) (200 AU) perpendicular to the direction of the outflow and \(~2''5\) (350 AU) along the outflow axis; the narrow dark lane between the scattered light lobes is \(~0''45\) (60 AU) thick. The observations are consistent with our initial modeling of a bright inner cavity separated by a dark lane due to extinction along the line of sight of the central protostar by the disk. The bright, compact scattered light might be due to complex inner structure generated by the outflow, as suggested in our first paper, or it may more likely be the upper layers of the disk forming from infalling matter.

Key words: ISM: individual objects (L1527) – ISM: jets and outflows – planetary systems – protoplanetary disks – stars: formation

Online-only material: color figure

1. INTRODUCTION

In the earliest stages of star formation, the Class 0/I phases (Andre et al. 1993; Lada 1987), the newborn protostar is embedded within a dense envelope of gas and dust. In the Class 0 phase, little or no emission is generally detected shortward of \(\sim 10\ \mu\text{m}\) due to high extinction toward the central object; however, the bipolar outflows from the central protostar and disk carve cavities in the envelopes creating scattered light emission, shifting the scattered light emission peak into the mid-IR (Tobin et al. 2007, 2008). The morphology of the outflow cavities then results from a ram pressure balance between the infalling envelope and outflow (Shu et al. 1991).

Early models of infalling envelopes assumed spherical collapse (Shu 1977) along with slow rotation (Ulrich 1976; Cassen & Moosman 1981; Terebey et al. 1984), which were later modified for infall from initially flattened geometries (Hartmann et al. 1996). The rotating collapse model provides a natural route for the formation of circumstellar disks within the protostellar envelope. However, disks in Class 0 objects have been difficult to study primarily because of the surrounding envelope (e.g., Jørgensen et al. 2009) and insufficient resolution at millimeter wavelengths to isolate the protostellar disk. In addition, the small-scale structure of outflow cavities in Class 0 protostars has also been elusive due to the envelope extincting near-IR scattered light emission, shifting the scattered light emission peak into the mid-IR (Tobin et al. 2007, 2008).

One of the nearest low-mass protostars in Taurus (\(d = 140\ \text{pc}\)), L1527 IRS (hereafter L1527), has been a favorite target for studies of outflow and envelope structure (e.g., Ohashi et al. 1997; Chandler & Richer 2000; Robitaille et al. 2007; Tobin et al. 2008; Gramajo et al. 2010). It has been classified as Class 0 protostar (Chen et al. 1995) but could be a Class I system given its edge-on orientation (Ohashi et al. 1997), which enhances the amount of extinction along the line of sight (Tobin et al. 2008). The moderate resolution Infrared Array Camera (IRAC) images of L1527 from Spitzer reveal bright bipolar cavities extending \(~10,000\ \text{AU}\) in radius (Hartmann et al. 2005; Tobin et al. 2008). The outflow cavities are separated by what appears to be a large-scale \(~1000\ \text{AU}\) dark lane; however, we observed a central point source between the cavities within the dark lane from 3.6 to 8 \(\mu\text{m}\). In Tobin et al. (2008, hereafter Paper I), we were able to explain this by constructing a model assuming that the point source was a compact inner outflow cavity, unresolved by Spitzer, connecting with the larger outer cavity. We then proposed high-resolution mid-IR imaging to test this model.

In this Letter, we present high-resolution L'-band (3.8 \(\mu\text{m}\)) observations of L1527 from the Gemini North telescope. This is the highest resolution mid-IR image of the inner envelope/outflow cavity around a Class 0 protostar. The observations confirm our prediction of a compact, bipolar scattered light structure; quite similar to the model constructed in Paper I but strongly resembling a disk in scattered light.

2. OBSERVATIONS AND DATA REDUCTION

We observed L1527 with the 8.1 m Gemini North telescope at Mauna Kea on 2009 October 24 and 2009 December 11 using the Near-Infrared Imager (NIRI; Hodapp et al. 2003) in L' band (3.8 \(\mu\text{m}\)). The camera was used in \(f/14\) mode which provides a \(0''049\ \text{pixel}^{-1}\) scale; we only used the central \(512 \times 512\) area of the detector for faster readout which enabled integrations short enough to avoid saturation from sky background. We observed with a five-point "dice-5" dither pattern with 5'' steps, and a nearby star was used for tip-tilt correction and guiding. At each position 150 co-added images of 0.2 s were taken; a total of 35 images were taken yielding 16 minutes of integration during the first observation and 176 images totaling 88 minutes of integration during the second observation. However, the first 38 images in the second observation were unusable due to variable sky background. Observations of the standard star HD 22068 show that the seeing was \(~0''3\) on both nights.

The raw data were reduced using the Gemini IRAF\(^3\) package. Flat-field images were generated from sky flats constructed by median combining the dithered images. Each on-source frame

\(^3\) IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.
was sky subtracted using a median sky generated from the on-source frame and the two images taken immediately before and after. This method of sky subtraction compensates for the rapid variations in sky brightness at $L'$ band. The sky-subtracted images were then combined using the imcombine task of IRAF using the offsets given in the header; L1527 was quite faint in the individual frames and could not be used for further refinement of the offsets. The data sets from both epochs of observation were combined yielding a final image with 85 minutes of integration.

We also include data taken with the IRAC (Fazio et al. 2004) on the Spitzer Space Telescope. These data were taken on 2004 February 24 as part of the GTO Taurus survey and were presented in Tobin et al. (2008) and Hartmann et al. (2005).

3. RESULTS

The images of L1527 at $L'$ band and 3.6 $\mu$m are shown in Figure 1. The IRAC image clearly shows the point-like structure appearing in the center of the envelope between the large scattered light cavities. The Gemini $L'$ image resolves the point-like structure into a compact, bipolar scattered light nebula at the center of L1527. The two lobes are separated by a narrow dark lane $\sim$0.45 (60 AU) wide, consistent with a circumstellar disk shadow. The $L'$ image reveals structure similar to that of the Hubble NICMOS images of Class I protostars in Taurus from Padgett et al. (1999). However, this is the first time such an image has been captured of a Class 0 protostar.

The total extent of the bipolar structure in the direction of the outflow (east–west) is $\sim$2:5 (350 AU) and $\sim$1:8 (250 AU) in width. The extent of the scattered light along the outflow and dark lane is much thicker than a prototypical disk (i.e., HH30; Burrows et al. 1996) indicating that the disk in L1527 is more vertically extended or that the scattering is coming from the inner envelope. The eastern lobe is about twice as bright as the western lobe; consistent with eastern side being slightly inclined toward us ($\sim$85°; Paper I). The orientation of the disk dark lane indicates that the rotation axis of the system has a position angle $\sim$85° east of north. We also see extended, low surface brightness outflow cavity emission extending away from the inner envelope in the Gemini image. The cavity is quite narrow until $\sim$6° (840 AU) from the center; this narrowness was not well resolved in the Spitzer image. Past 6°, the cavity expands rapidly to very wide angles. The total flux within a 7:14 (1000 AU) aperture radius is 6.5 ± 0.6 mJy, consistent with the IRAC flux from Paper I.

3.1. Models

We use the Monte Carlo radiative transfer code of Whitney et al. (2003) to interpret the observations. The model components are described in Paper I, but we discuss some important aspects here for completeness. The envelope density structure is the standard rotating collapse solution (Cassen & Moosman 1981; Terebey et al. 1984) in which envelope density scales with the infall rate $M_{\text{env}}$ with $\rho \propto R^{-1/2}$ outside the centrifugal radius ($R_C$) and $\rho \propto R^{-1/2}$ inside $R_C$. Curved outflow cavities are carved out of the envelope; their shape is defined by a polynomial $z \propto (x^2 + y^2)^{b/2}$, where the degree of the polynomial ($b$) is the shape parameter. We use the dust model from Paper I for the envelope which has grains up to 1 $\mu$m in radius.

The disk is defined by its initial scale height $H_0$ at the stellar radius $R_s$ and flaring power law $H \propto R^\beta$, radial density profile $\rho \propto R^{-\alpha}$, mass, and outer radius. The vertical structure of the disk is assumed to be Gaussian with an initial scale height defined to be in hydrostatic equilibrium at the dust destruction radius ($T_d = 1600$ K). Values of $\beta = 9/8$, 5/4 are commonly used, corresponding to isothermal scale heights with $T_{\text{disk}} \propto R^{-3/4}$ and $R^{-1/2}$. The gas and dust of the disk are assumed to be well mixed. The dust opacities for the disk are taken from Wood et al. (2002) which were used to model the spectral energy distribution (SED) of HH30. The dust is distributed in a quasi-settled manner with grains up to 1 mm in the disk mid-plane while smaller grains remain extended. The transition between these dust populations is defined to be $n_{H_2} = 10^{10}$ cm$^{-3}$ or the first scale height.
Figure 2. Comparison of models to the observations. Top row: observations of L1527 from Spitzer and Gemini. Middle row: initial model of L1527 from Paper I without any knowledge of L1527 at high resolution. Bottom row: disk plus single-cavity model. Note that the refined dual-cavity model images are not shown as they are nearly identical to the disk models.

In Paper I, we inferred that the apparent point source seen at 3.6 μm was in fact a bipolar structure seen in reflected light, with the true central source actually hidden by extinction. To create this structure, we constructed a dual-cavity model having a narrow inner cavity with an outer cavity offset by 100 AU (see Figure 10 of Paper I for an illustration). Comparing the top and middle rows of Figure 2 shows that our prediction was qualitatively correct. We next take advantage of the high-spatial resolution of the Gemini data to improve our understanding of the inner structure. We required that models reproduce both the L’ and IRAC images and the broadband SED and Infrared Spectrograph (IRS) spectrum (Furlan et al. 2008; Paper I), as it is important to use as many constraints as possible (Paper I; Gramajo et al. 2010).

We first adjusted the parameters of the dual-cavity model to better reproduce the Gemini observations by varying the inner and outer cavity shapes and opening angles. As shown in Figures 2 and 3, our best-fit dual-cavity model reproduces the observations reasonably well (note that the images for the refined dual-cavity model are not shown as they nearly identical to the disk model as discussed below). The envelope infall rate for this model was $10^{-5} \, M_\odot \, yr^{-1}$; the outer cavity was offset from the inner cavity by 85 AU. The disk parameters are $H(10 \, AU) = 1.87 \, AU$ with $\beta = 1.25$, $H_0 = 0.0332 \, R_*$, $M_{disk} = 0.05 \, M_\odot$, and $R_{disk} = 25 \, AU$; a model with $\beta = 1.125$ was also able to be fit, but with double the initial scale height; the full parameter set is listed in Table 1.

We did not consider a disk model in Paper I because the large-scale dark lane seemed to be too thick to be reproduced with a disk. However, using the detailed Gemini image, we can describe disk parameters which yield scattering surfaces comparable to that of the dual-cavity model. The highly flared disk in this model had $H(10 \, AU) = 1.95 \, AU$ with $\beta = 1.25$, $H_0 = 0.03 \, R_*$, $M_{disk} = 0.05 \, M_\odot$, and $R_{disk} = 25 \, AU$. The envelope infall rate was lowered to $0.8 \times 10^{-5} \, M_\odot \, yr^{-1}$ in order to allow more scattered light from the disk to escape through the envelope. We also used the envelope dust model for the disk upper layers rather than the
default dust model; this increased the $L'$ intensity and reduced emission from 10 to 60 $\mu$m (see Table 1 for other parameters) bringing the model into closer agreement with the observations. As shown in Figures 2 and 3, this model also provides reasonable agreement with the observations.

4. DISCUSSION

The dual-cavity model in Paper I was justified based on simulations with a wide-angle outflow and a highly flattened envelope density distribution (Delamarter et al. 2000). However, it is unclear if such a flattened envelope is present in L1527, as there is no evidence for this in submillimeter observations (Chandler & Richer 2000). In addition, the outflow cavity on scales larger than 840 AU from the central object does not easily fit within this framework due to the rapid widening of the scattered light nebula beyond 840 AU (Section 3; Figure 1). This is difficult to explain with a simple conical cavity because there is no direct line of sight from the protostar/disk to these parts of the outflow cavity. Therefore, we suggest that the morphology of the scattered light nebulosity on large scales is not due directly to the outflow but to the morphology of the envelope and/or ambient medium (Tobin et al. 2010). In any case it appears difficult to explain the complex shape of the scattered light structures with a simple outflow–envelope interaction.
Given these difficulties, the disk scenario seems attractive. Images of disks in silhouette have previously been observed around T Tauri stars (Class II sources) and Class I protostars (e.g., Padgett et al. 1999; Burrows et al. 1996). The small-scale scattered light morphology of L1527 bears a resemblance to that of IRAS 04302+2247 and HH30. The problem for this model is that the disk must be highly flared, with the aspect ratio of the disk extinction lane relative to the extent of the scattered light surfaces being about a factor of two larger than other objects. To reproduce the compact scattered light and large-scale dark lane with a disk, it was necessary to adopt a high degree of flaring in the disk ($\beta = 1.27$), a steep density profile ($\alpha = 3.0$), a large disk radius ($R_d = 190$ AU), and a small disk mass ($M_d = 0.005 M_\odot$).

(Note that the mass is simply a formal parameter of the model for scaling the density. Extrapolating disk masses from fitting scattered light in the disk upper layers is problematic since they contain a small fraction of the total mass.) These observations and modeling emphasize not only that disks form early during protostellar collapse (Jørgensen et al. 2009; Vorobyov 2009) but also that disks with large radii are able to form during the Class 0 phase (see also Enoch et al. 2009) with radii comparable to Class II disks in Taurus (Andrews & Williams 2007).

In general, dust growth and/or depletion in upper disk layers relative to interstellar medium conditions is needed to reproduce the scattered light images of edge-on disk systems and the SEDs of T Tauri stars (D'Alessio et al. 2006; Duchêne et al. 2010; Furlan et al. 2008). Thus, it may be that the postulated L1527 disk has had much less dust evolution and thus has more small dust in upper layers, making it easier to explain the wide extinction lane observed (e.g., D'Alessio et al. 2006).

Loinard et al. (2002) directly imaged the disk of L1527 and a binary companion separated from the primary by 0′17 (24 AU) with Very Large Array (VLA) $\lambda = 7$ mm observations. These observations are overplotted on the $L'$ image in Figure 4. The observed disk is quite compact—only $\sim 0.3$ (40 AU) in diameter. Though this system is a close binary, we do not expect the companion to affect the modeled parameters significantly, because our results mostly constrain the outer disk. The compactness of the disk measured (Loinard et al. 2002) is not inconsistent with our disk model since the $\lambda = 7$ mm observations will only be sensitive to the densest part of the disk and where the grains are largest. Their measured disk mass of $0.1 M_\odot$ is substantially larger than our disk model (which is uncertain as discussed previously). Note that the disk mass is strongly dependent on the assumed dust mass opacities; Loinard et al. (2002) used a dust opacity model based on Pollack et al. (1994) which had $\kappa_{7mm} = 4.9 \times 10^{-4}$ cm$^2$ g$^{-1}$ (P. D'Alessio 2010, private communication). Andrews & Williams (2005) used $\kappa_{80\mu m} = 0.035$ cm$^2$ g$^{-1}$ with $\kappa \propto \lambda^{-1}$ which yields $\kappa_{7mm} = 0.00425$ cm$^2$ g$^{-1}$ when extrapolated. The difference between the $\kappa_{7mm}$ values can be attributed to the Pollack et al. (1994) dust model only considering grains up to 1 $\mu$m in size while the dust model used by Andrews & Williams (2005) considered grains up to 1 mm in size. Scaling the Loinard et al. (2002) $\lambda = 7$ mm mass to $\kappa_{7mm}$ from Andrews & Williams (2005) gives $M_{\text{disk}} = 0.0095 M_\odot$, in agreement with the mean disk mass of Taurus.

From the observations and modeling it is now clear that the small-scale scattered light in L1527 is most likely due to a disk. However, the assumed parameters needed to fit the disk model (e.g., steep density profile) may only have been necessary to enable our simplistic treatment of disk structure to work for L1527. Models that solve for the vertical structure of the disk self-consistently (i.e., D'Alessio et al. 1998), given the irradiation from the central object, have a density structure that is not Gaussian (as assumed in our modeling) but falls off less rapidly with $z$ because the temperature increases with vertical height $z$. Indeed, even in the context of an isothermal structure, the Gaussian density distribution becomes a poor approximation as the ratio of the vertical height to radial distance becomes $z/R \rightarrow 1$. These issues deserve further investigation with physically self-consistent radiative transfer modeling of L1527.

4.1. Conclusions

We have presented high-resolution $L'$ imaging of the inner envelope of L1527 demonstrating that much can be learned of inner envelope structure and newly forming disks with high-resolution scattered light observations of Class 0 protostars. The observations strongly resemble the dual-cavity model constructed in Tobin et al. (2008); however, the observations can be equally well reproduced by a large, highly flared disk or a refined dual-cavity structure. However, the global scattered light structure is difficult to interpret as purely an outflow cavity. We therefore suggest that the bright scattered light structure is most likely be a vertically extended disk-in-formation with material falling onto it.

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