ASTRONOMY

First detection of equatorial dark dust lane in a protostellar disk at submillimeter wavelength

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In the earliest (so-called "Class 0") phase of Sun-like (low-mass) star formation, circumstellar disks are expected to form, feeding the protostars. However, these disks are difficult to resolve spatially because of their small sizes. Moreover, there are theoretical difficulties in producing these disks in the earliest phase because of the retarding effects of magnetic fields on the rotating, collapsing material (so-called "magnetic braking"). With the Atacama Large Millimeter/submillimeter Array (ALMA), it becomes possible to uncover these disks and study them in detail. HH 212 is a very young protostellar system. With ALMA, we not only detect but also spatially resolve its disk in dust emission at submillimeter wavelength. The disk is nearly edge-on and has a radius of ~60 astronomical unit. It shows a prominent equatorial dark lane sandwiched between two brighter features due to relatively low temperature and high optical depth near the disk midplane. For the first time, this dark lane is seen at submillimeter wavelength, producing a "hamburger"-shaped appearance that is reminiscent of the scattered-light image of an edge-on disk in optical and near infrared light. Our observations open up an exciting possibility of directly detecting and characterizing small disks around the youngest protostars through high-resolution imaging with ALMA, which provides strong constraints on theories of disk formation.

INTRODUCTION

Stars are formed inside molecular cloud cores through gravitational collapse. However, the details of the process are complicated by the presence of magnetic fields and rotation. In theory, rotationally supported circumstellar disks are expected to form inside collapsing cores around protostars, feeding the protostars. These disks have been detected with radii of up to ~500 astronomical unit (AU) in the late (that is, Class II or T Tauri) phases of Sun-like star formation (*1*, *2*). These disks must have started in the earliest (Class 0) phase, as observed in a few Class 0 sources, for example, HH 211 (*3*), L1527 (*4*) and, recently, VLA 1623 (*5*). However, those disks, with radii of <150 AU, have not been well resolved spatially, especially in the vertical direction, because of insufficient resolution.

In models of nonmagnetized core collapse, a circumstellar disk can form as early as in the Class 0 phase (*6*). However, a realistic model should include magnetic fields because molecular cores are found to be magnetized (*7*). In the presence of a dynamically important magnetic field, when and how disks form become uncertain because the field can efficiently remove the angular momentum of the collapsing material, leading to the so-called "magnetic braking catastrophe" in disk formation (*8*). In those cases, a flattened envelope (that is, pseudodisk), but not a large rotationally supported disk, can form around the central source (*9*). A misalignment between the magnetic field and the axis of rotation (*10*, *11*) and the nonideal magnetohydrodynamic (MHD) effects (*12*) can sometimes solve this catastrophe. Even when a disk is formed, if a significant fraction of the magnetic flux of the dense core is dragged into it, the disk would rotate at a sub-Keplerian speed because of magnetic support (*13*).

HH 212 is a nearby protostellar system deeply embedded in a compact molecular cloud core in the L1630 cloud of Orion at a distance of ~400 pc. The central source is the Class 0 protostar IRAS 05413-0104, with a mass of ~0.2 to 0.3 $M_\odot$ (solar mass) (*14*, *15*) and a bolometric luminosity $L_{\rm bol}$ of ~9 $L_\odot$ (luminosity of the Sun) (updated for the distance of 400 pc) (*16*). It is very young, with an estimated age of only ~40,000 years (*14*), and drives a powerful bipolar jet (*17*). According to current jet models (*18*, *19*), a circumstellar disk is required to launch the jet. Recent observations at a resolution of ~ 0″.5 (200 AU) show a flattened envelope and a tentative compact disk around the central source in dust continuum at 850 μm (*14*). The gas kinematics in HCO^+ show that the flattened envelope is infalling with small rotation (that is, spiraling) to the central source, which is expected for the pseudodisk in the models of magnetized core collapse (*9*). Inside this structure, the HCO^+ and $C^{17}O$ kinematics indicate the presence of a rotationally supported circumstellar disk around the central source, with a radius of ≤100 AU (*14*, *15*). Here, we report the Atacama Large Millimeter/submillimeter Array (ALMA) observations in dust emission at ~850 μm that clearly resolves the disk spatially.

RESULTS

Figure 1A shows the inner part of the jet within ~12,000 AU (30″) of the source, where it was mapped in H_2 with the Very Large Telescope at a resolution of ~0″.35 (*20*) and in SiO and CO with ALMA at a resolution of 0″.5 (*21*), to show the physical relationship of the envelope/disk with the jet. The jet is highly collimated with a position angle (PA) of ~23°. Here, a reflection nebula is also seen in continuum at 2.12 μm in the infrared near the source, with a dust lane roughly perpendicular to the jet axis. This dust lane is due to dust extinction of the extended envelope detected in NH_3 (*22*). The jet was not detected in H_2 near the source because of the same dust extinction. However, it was clearly detected in SiO down to the central source (Fig. 1B).

At submillimeter wavelength, dust extinction from the envelope is negligible, and thus, we can detect the dust emission down to the small scales at which the circumstellar disk is formed. Previously, a flattened envelope was detected in continuum at 850 μm, deep inside the extended envelope within ~1000 AU of the central source at a resolution of ~0″.5 (200 AU) (Fig. 1, A and B) (*14*). Zooming in to the center at a higher resolution of ~0″.1 (40 AU) (Fig. 1C), we see the inner part of the envelope extending along the major axis with a PA of ~123° (as indicated by

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the white lines), roughly perpendicular to the jet axis. Zooming in further to the center at an unprecedented resolution of ~0″.02 (8 AU) (Fig. 1D), we see the central peak being resolved into a bright disk-like structure with a major axis at a PA of ~113° (as indicated by the white lines), exactly perpendicular to the jet axis. At this high resolution, the noise level becomes ~0.08 mJy (millijansky) beam^{-1} (see the Supplementary Materials); therefore, the envelope, with a flux density of <0.11 mJy beam^{-1} (estimated from Fig. 1C), cannot be detected. There is a big jump (by a factor of ~10) in the brightness temperature (hereafter, T_b) from ~3 K (or 3 mJy beam^{-1} in a 0″.1 beam in Fig. 1C) in the innermost envelope to ~30 K (or 1.1 mJy beam^{-1} in a 0″.02 beam in Fig. 1D) in the outer part of the disk-like structure, indicating that the disk-like structure is physically distinct from the envelope and thus can be naturally identified as the circumstellar disk. As discussed below, because the emission in the outer disk is becoming optically thick, the density in the outer disk is expected to be more than 10 times higher than that in the innermost envelope. This jump could be due to the density jump produced by an accretion shock in disk formation (*14*, *23*).

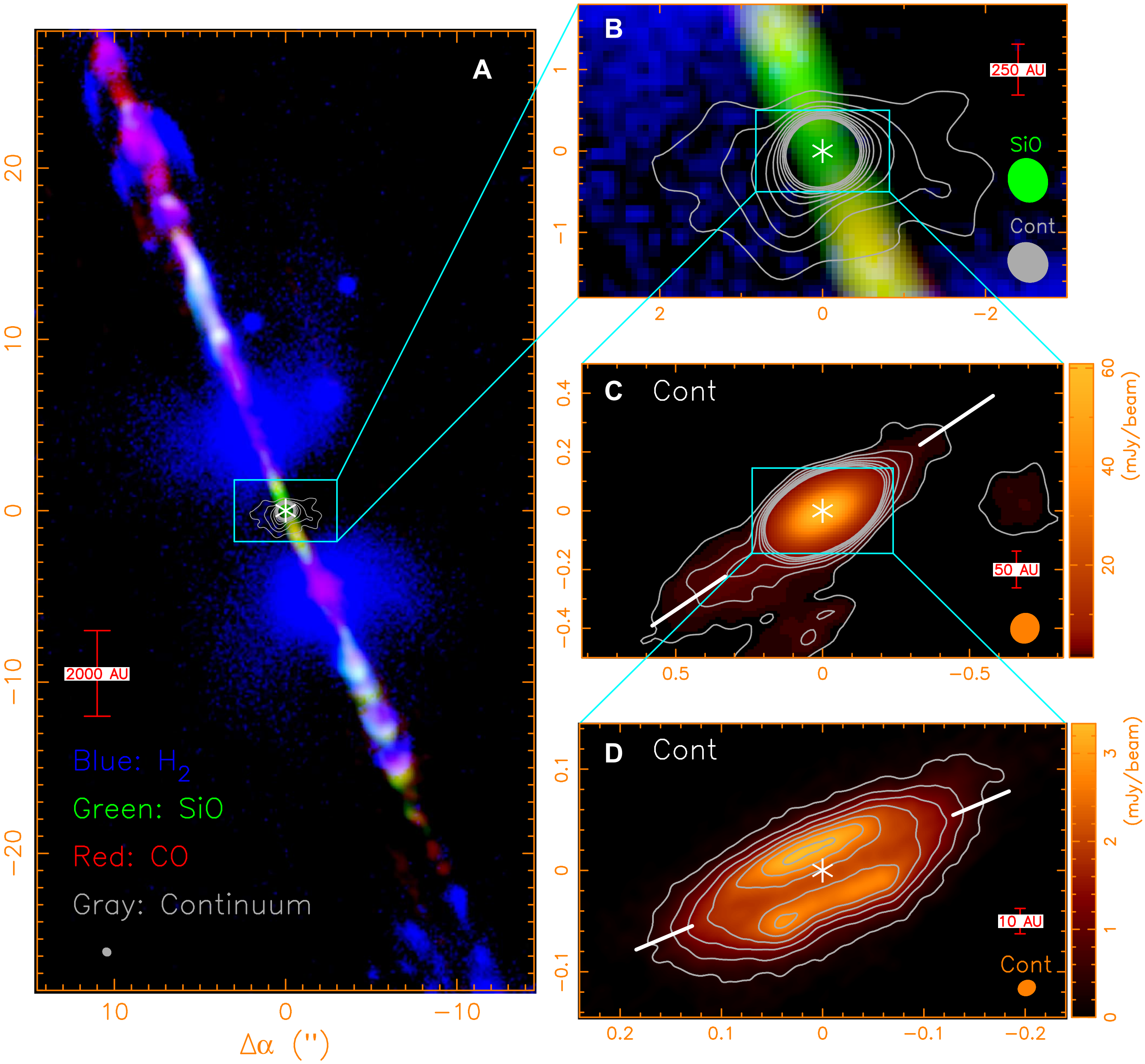

Fig. 1. ALMA maps of the jet, envelope, and disk in the HH 212 system. (**A**) A composite image for the inner part of the HH 212 jet: blue represents the map of H_2 + the 2.12-μm continuum, obtained with the Very Large Telescope (*20*), and green and red represent the SiO and CO maps, respectively, obtained with ALMA (*21*). Gray contours show the continuum map of the envelope/disk at 850 μm, obtained with ALMA at a resolution of ~0″.5 (*14*). Contours start at 3.125 mJy beam^{-1} with a step of 3.75 mJy beam^{-1}. (**B**) A zoomed-in image to the center for the jet and envelope/disk. (**C**) A zoomed-in image to the center of the continuum at a resolution of ~0″.1. Contours start at 1.23 mJy beam^{-1} with a step of 0.62 mJy beam^{-1}. (**D**) A zoomed-in image to the center of the continuum at a resolution of ~0″.02. Contours start at 0.29 mJy beam^{-1} with a step of 0.49 mJy beam^{-1}. Asterisks mark the possible source position at $\alpha_{(2000)}$ = 05h43m51s.4086, $\delta_{(2000)}$ = −01°02′53″.147, obtained by comparing to the model in Fig. 3.

Being perpendicular to the jet, the disk must be nearly edge-on with the nearside tilted to the southwest because the jet has a small inclination angle of ~4° ± 2° to the plane of the sky (*24*, *25*), with the northeastern component tilted slightly toward us. A prominent dark lane is seen running along the major axis of the disk. The thickness of the dark lane increases with the increasing distance from the center, giving the impression that the disk is flared, although detailed modeling is required to ascertain whether this is the case. A cut along the dark lane shows that the flux density increases rapidly from ~0.4 mJy beam^{-1} (T_b, ~11 K; 5 σ) at ~68 AU (0″.17) to ~1.8 mJy beam^{-1} (T_b, ~50 K) at ~40 AU (0″.1) and then slowly increases to ~ 2.1 mJy beam^{-1} (T_b, ~58 K) at the center (see Fig. 2), suggesting that the emission is optically thick along the dark lane, except near the edge. This suggests that millimeter-size particles may dominate the emission. The half-width at half maximum of the intensity profile is ~60 AU (0″.15). The dark lane is sandwiched by two brighter regions: one above at ~3.3 mJy beam^{-1} (T_b, ~90 K) in the northeast and one below at ~2.9 mJy beam^{-1} (T_b, ~80 K) in the southwest. These two regions are from the surface of the disk. They are brighter because the disk surface is expected to be warmer than the midplane due to radiation heating of the central protostar (*26*) and possible interaction of the disk surface with the wind from the innermost disk (*27*). Because the nearside of the disk is tilted slightly to the southwest, the emission in the northeast is less absorbed by the nearside of the disk and is thus brighter than the emission in the southwest.

DISCUSSION

Previous observations of the disk emission at 1.4 and 0.85 mm suggested a spectral index of ~2.6 (*28*) and thus a dust opacity spectral index β of ~0.6, similar to the values often obtained for disks in more evolved (Class II) objects (*29*). This β value indicates that grain growth to millimeter size or larger (*30*) has started early in the formation of the disk, or perhaps even before this phase, and that dust scattering is expected to significantly contribute to the disk emission in submillimeter wavelengths (*31*). Dust scattering should produce continuum polarization that, if detected, can provide an independent probe of the grain properties, especially their sizes (*31*). The total flux of the disk emission is ~157 mJy. If the emission is optically thin and all thermal at temperature of 50 K, then the disk mass is ~0.014 $M_\odot$ for a dust opacity of 0.054 cm^2 g^{-1} at 850 μm (*32*). However, this estimate is quite uncertain because of the large uncertainty in dust opacity and potential effects of dust scattering and because the emission in the outer disk is becoming optically thick.

To more quantitatively illustrate how the most important feature observed in HH 212, a dark lane sandwiched by two brighter regions (that is, the "hamburger" appearance), may arise physically, we constructed a simple toy model for disk emission in submillimeter wavelength. The model is described in the Supplementary Materials. Briefly, the distributions of the density and temperature of the disk are prescribed, with the surface warmer than the midplane at a given radius. Figure 3 shows the emission at 850 μm for the model disk. It broadly reproduces the major features observed in the HH 212 disk, including the dark lane and the bright regions above and below the lane, with the above emission brighter than that below. In this particular example, the dark lane comes from the cooler outer part of the disk that becomes optically thick at a radius of ~40 AU (0″.1), and the brighter emission above and below the lane is due to the warmer surfaces of the inner disk, in agreement with expectation 2. We refrain from drawing quantitative conclusions about the disk parameters from the model, except to note that the radius of the model disk (68 AU) is not far from that estimated on the basis of the intensity profile in Fig. 2 (~60 AU) and that the disk mass (0.05 $M_\odot$) is also consistent with the minimum mass estimated under the optically thin assumption (0.014 $M_\odot$). To do better, major refinements would be needed, including a self-consistent determination of the density and temperature structures and a treatment of dust scattering, which is expected to be important for large grains.

Our observations show the first equatorial dark dust lane in a protostellar disk in the earliest phase of star formation. The detection is made possible by the unprecedented resolution achieved by the ALMA long baseline. The prominent dark lane and the large brightness contrast with the envelope are strongly suggestive of the disk-like structure being a rotationally supported disk. There is already strong indication of a Keplerian disk inside 100 AU of the protostar from molecular line observations (*14*, *15*). During the earliest phase of star formation, the disks are expected to be rather small but possibly massive, which makes them likely to be optically thick and the velocity profile difficult to measure, at least in the relatively short-wavelength ALMA bands that are needed to resolve the (small) disks. In this case, the dust continuum may be the only viable way to detect and characterize these youngest protostellar disks. Our resolved observations of the HH 212

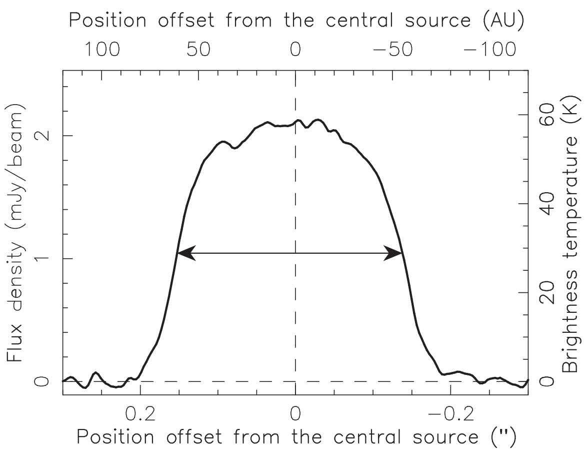

Fig. 2. Flux density (and corresponding brightness temperature) of the continuum cut along the dark lane. The vertical dashed line indicates the source position. The double-headed arrow marks the full-width at half maximum of the intensity profile.

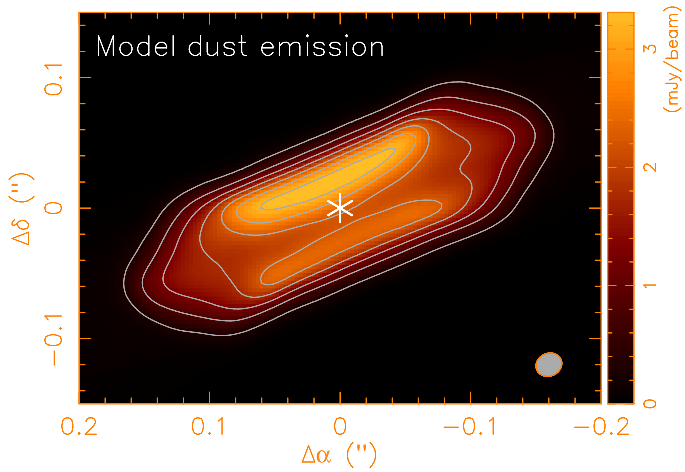

Fig. 3. Simulated observed continuum emission at 850 μm derived from the model. Contour levels are the same as in Fig. 1D.

disk demonstrated that it is possible, at least for nearly edge-on systems. It raises the exciting possibility of detecting even smaller disks around deeply embedded protostars. If small disks of tens of AUs (or smaller) turn out to be common around the earliest protostars, it would imply that the magnetic braking catastrophe in the theoretical literature of disk formation is averted early on, plausibly through nonideal MHD effects, which are expected to be most efficient at decoupling the magnetic field from the bulk material close to the central star where the density is the highest (*33*). Just as importantly, our observations open a window on the vertical structure of the disks around deeply embedded protostars in the earliest (Class 0) phase, which could ultimately be compared to those surrounding more evolved young stars (Class I sources and T Tauri stars), potentially yielding key insights into the processes of grain growth and settling that are important to planet formation.

MATERIALS AND METHODS

Observations of the HH 212 protostellar system were carried out with ALMA in band 7 at ~350 GHz in cycles 1 and 3, with 32 to 45 antennas and projected baselines ranging from ~15 to 16,200 m. The total time on the HH 212 system was ~148 min. We also introduced a parameterized model for the disk emission in HH 212 to illustrate the formation of the dark lane sandwiched between two brighter regions. Details of our data reduction and radiative transfer modeling are provided in the Supplementary Materials.

SUPPLEMENTARY MATERIALS

Supplementary material for this article is available at http://advances.sciencemag.org/cgi/content/full/3/4/e1602935/DC1
Supplementary Materials and Methods
table S1. Observation logs.
table S2. Correlator setup for cycle 1 project.
table S3. Correlator setup for cycle 3 project.
table S4. Calibrators and their flux densities.
References (*34*–*36*)

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Acknowledgments: We made use of the following ALMA data: ADS/JAO.ALMA#2012.1.00122.S and ADS/JAO.ALMA#2015.1.00024.S. ALMA is a partnership of the European Southern Observatory (ESO) (representing its member states), NSF (USA), and the National Institutes of Natural Sciences (Japan), together with the National Research Council (Canada), the National Science Council and Academia Sinica Institute of Astronomy and Astrophysics (Taiwan), and the Korea Astronomy and Space Science Institute (Republic of Korea), in cooperation with the Republic of Chile. The Joint ALMA Observatory is operated by ESO, the Associated Universities Inc./National Radio Astronomy Observatory), and the National

Astronomical Observatory of Japan. **Funding:** C.-F.L. acknowledges grants from the Ministry of Science and Technology (MOST) of Taiwan (104-2119-M-001-015-MY3) and the Academia Sinica (Career Development Award). Z.-Y.L. is supported, in part, by NSF (AST1313083) and the National Aeronautics and Space Administration (NNX14AB38G), and N.H. is supported in part by MOST (105-2112-M-001-026). **Author contributions:** C.-F.L. led the project, analysis and discussion and drafted the manuscript. Z.-Y.L. participated in the analysis and discussion and commented on the manuscript. All other authors contributed to the scientific discussion. **Competing interests:** N.H. is one of the members of the ALMA Proposal Review Committee (2014). All other authors declare that they have no competing interests. **Data and materials availability:** Our ALMA data can also be obtained from the ALMA science data archive (https://almascience.nao.ac.jp/alma-data). All other data needed to evaluate the conclusions in the paper are present in the paper and/or the Supplementary Materials. Additional data related to this paper may be requested from the authors.

Submitted 23 November 2016
Accepted 16 February 2017
Published 19 April 2017
10.1126/sciadv.1602935

Citation: C.-F. Lee, Z.-Y. Li, P. T. P. Ho, N. Hirano, Q. Zhang, H. Shang, First detection of equatorial dark dust lane in a protostellar disk at submillimeter wavelength. *Sci. Adv.* **3**, e1602935 (2017).