Inner Rim of A Molecular Disk Spatially Resolved in Infrared CO Emission Lines[1]

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ABSTRACT

We present high-resolution infrared spectroscopy of the Herbig Ae star HD 141569 A in the CO $v = 2 - 1$ transition. With the angular resolution attained by the adaptive optics system, the gas disk around HD 141569 A is spatially resolved down to its inner-rim truncation. The size of the inner clearing is 11±2 AU in radius, close to the gravitational radius of the star. The rough coincidence to the gravitational radius indicates that the viscous accretion working together with the photoevaporation by the stellar radiation has cleared the inner part of the disk.

Subject headings: circumstellar matter — planetary systems: formation — planetary systems: protoplanetary disks — stars: formation — stars: individual (HD 141569 A) — infrared: stars

1. Introduction

Direct imaging of circumstellar disks is one of the most rapidly developing fields of observational astronomy (e.g. Grady et al. 2005). It faces, however, two barriers in the

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optical/infrared: it is mostly sensitive to the dust grain either in scattered light or thermal emission, although dust carries only a fraction of the mass with all the rest in the gas phase mostly in molecular form. Moreover, it probes only outer regions of a disk, being obstructed by glaring light from the central star. However, it is this invisible part of the disk, gas inside 30 AU of the star, that has direct consequence to the gas giant planet formation. The gas dissipation at the inner disk practically limits its time scale, and make a critical test to the current planet formation theories that predict distinct time scales to build up Jupiter-like planets ($\sim 10^7$ yr, Pollack et al. 1996; $\sim 10^5$ yr, Boss 2002).

Molecular spectroscopy in the near-infrared has a particular advantage in this area. The energy gap between the ground state and the vibrationally excited states is on the order of 10^3 K, which automatically guarantees that the gas in emission is in the innermost part of the disks. The molecular spectroscopy also ensures that the emission does not arise as close as in the stellar photosphere where the temperature is too high to keep the molecules from dissociation. The CO molecule has been the popular spectroscopic tracer of the gas disks both at the first overtone at 2.3 μm (Geballe & Persson 1987; Carr 1989; Chandler, Carlstrom, & Scoville 1993; Najita et al. 1996; Biscaya et al. 1997; Kraus et al. 2000; Bik & Thi 2004; Blum et al. 2004; Thi et al. 2005), and the fundamental band at 4.7 μm (Brittain et al. 2003; Najita, Carr, & Mathieu 2003; Blake & Boogert 2004; Rettig et al. 2004; Carmorna et al. 2005).

HD 141569 A is a Herbig Ae star in transition to a debris disk object with an optically thin disk with relatively small infrared excess ($L_{\rm IR}/L_* = 8 \times 10^{-3}$ by Sylvester et al. 1996; cf. $L_{\rm IR}/L_* = 2.4 \times 10^{-3}$ of β Pic by Heinrichsen et al. 1999). The dust disk around HD 141569 A has been directly imaged with coronagraphy by *HST* in the scattered light at the visible and the near-infrared wavelengths (Augereau, Lagrange, & Mouillet 1999; Weinberger et al. 1999; Mouillet et al. 2001; Clampin et al. 2003), as well as a ground-based telescope with adaptive optics system (Boccaletti et al. 2003). The position angle of the disk is $356° \pm 5°$ east from north in projection on the sky (Weinberger et al. 1999). The disk ellipse in the thermal emission is well aligned to the dust scattered light ($355° \pm 19°$ by Fisher et al. 2000; $354° \pm 4°$ by Marsh et al. 2002). The residual gas in the outer disk has been detected in the radio spectroscopy at CO $J = 1 - 0$ and $J = 2 - 1$ ($M_{\rm H_2} = 300\ M_\oplus$, Zuckerman, Forveille, & Kastner 1995; Dent, Greaves, & Coulson 2005). The line emission CO $J = 2 - 1$ is recently spatially resolved by Dutrey, Lecavelier Des Etangs, & Augereau (2004) with red- and blue-shifted components split in north and south of the star with a velocity interval indicative of gas orbital motion.

HD 141569 A is exceptional among Herbig Ae/Be stars for its CO $v = 2 - 1$ emission. The infrared transition $v = 2 - 1$ manifests the molecules are first electronically excited by the UV irradiation. Brittain et al. (2003) argues that the absence of high velocity wings in CO $v = 2-1$ indicates that the line emission comes from the inner-rim of the disk receded from the star by 17 AU, where the disk wall is directly illuminated. The presence of inner clearing of the size of 10–20 AU is consistent with the lack of near-infrared excess in the infrared energy distribution (Sylvester et al. 1996), and the mid-infrared imaging implying disk within 30 AU is already cleared to some extent (Marsh et al. 2002). The size of the inner hole is well within the reach of spatially resolved observations with adaptive optics systems at 8-m class telescopes at the distance of the star (d =99–108 pc, van den Ancker et al. 1998; Merín et al. 2004; hereafter we take d =108 pc from Merín et al). The goal of this paper is to present such directly resolved observations of this inner clearing in CO $v = 2-1$ transitions.

2. Observation and Data Reduction

The spectroscopic observation was carried out on 25 May 2005 UT at the Subaru Telescope with the facility spectrograph IRCS (Tokunaga et al. 1998; Kobayashi et al. 2000). The curvature sensing adaptive optics system was used to feed nearly diffraction-limited images to the spectrograph (Gaessler et al. 2002; Takami et al. 2004). HD 141569 A (R=7.02; Merín et al. 2004) itself was used as the wavefront reference source at the visible wavelength. The grating angles were set so that the two echelle bands at 4.597–4.718 μm and 5.014–5.147 μm were covered in the 1k×1k InSb array. The first band includes the R-branch of CO $v = 2-1$ at $R(0)$ to $R(15)$. The resolving power of R =20,000 (Δv =15 km s^{-1}) was attained with a $0''.15 \times 7''.5$ slit. The plate scale along the slit is 60 mas/pixel. The slit was oriented to north to south, parallel to the major axis of the disk on the sky. The data were recorded by switching the field of view by $3''$ in every 5 minutes along the slit with the tip-tilt mirror inside the adaptive optics system to subtract the sky emission. The total integration time is 20 minutes. The spectroscopic flat field was obtained at the end of the night from a halogen lamp exposure. The seeing was modest, $0''.9$ at R, during the observation.

Two-dimensional spectrograms were reduced in the standard manner with the IRAF[1] image reduction package, involving sky-subtraction, flat-fielding, and interpolation of outlier pixels. The wavelength calibration was carried out by maximizing the cross-correlation between the observed spectra and the atmospheric transmission curve calculated by ATRAN

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[1] IRAF is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

(Lord 1992). The tilt of the dispersion axis with respect to the array column, and the geometrical distortion, i.e., the curvature of the slit image on the detector array, was corrected so that the dispersion and the telluric emission lines show up straight to the detector vertical and horizontal over whole spectral range. A part of the spectrogram after the correction of spectral and spatial distortions is shown in Figure 1.

The CO line emission at $v = 2 - 1$ within our spectral coverage is all found spatially extended up to 50 AU beyond the photospheric emission of the star. In order to isolate the molecular lines from the stellar photospheric emission, one-dimensional point spread function (PSF) was taken from the nearby continuum, and was subtracted from the line emission. Note that the spectral PSF, although spatially one dimensional, provides almost an ideal PSF: it is recorded by the same instrument at the same time at nearly identical wavelengths to the line emission. The size of the PSF measured at the continuum wavelength was $0\farcs24$ in full width at half maximum. Caution was taken at the scaling of the PSF, since over-subtraction of the PSF introduces an artificial depression at the center, which is possibly mistaken for a disk inner hole. First, one dimensional spectrum was extracted inside a small aperture matched to the PSF to sample the stellar continuum flux exclusively. The one dimensional spectrum was smoothly interpolated from the both sides of a line to measure the continuum contribution at the line wavelength. The PSF was scaled to the height of the continuum flux, and subtracted from the line emission accordingly (Figure 1).

We briefly discuss the influence of the telluric absorption below. The energy loss in absorption in the telluric atmosphere has to be compensated to restore the absolute flux in the line emission. The radial profile is, on the other hand, less subject to the atmospheric effect, as long as the emission line stays at constant wavelength along the radius. However, because of the finite displacement in the line velocity by the gas orbital motion, the emission lines still have to be at reasonably flat part of the transmission curve. Fortunately the interference of the telluric absorption is less severe at CO $v = 2 - 1$ than CO $v = 1 - 0$ in which the telluric atmosphere has corresponding absorption lines. Since apparent gas velocity at 5 AU and 20 AU is 15 km s^{-1} and 7 km s^{-1} respectively, if it is in the Keplerian rotation, a flat part of $\Delta v \approx 8$ km s^{-1} would suffice for the radial profile to be intact. Those lines longword of 4.68 μm that seriously overlap with the telluric absorption lines with the clearance less than this interval were discarded, and the lines from $R(5)$ to $R(9)$ were only used for the further analysis, at reconstruction of the radial profile and the line image shown in Figure 2 and 3.

3. Result

Each line image was summed up together along the dispersion axis by ±19 km s^{-1} to reconstruct a one-dimensional disk radial profile. The central depression is clearly resolved in the combined profile in Figure 2. Since the individual line image is considered as an independent imaging, the error bars were given by the standard deviation of the radial profiles at different transitions. A power-law radial profile with an inner cut-off at r_i ($f(r) \propto r^{-\beta}$ at $r \geq r_i$, $f(r) = 0$ at $r < r_i$) was fit to the observation after convolved with the system PSF. The best-fit radius of the central clearing is found at r_i =11±2 AU with the power-law index β =2.6±0.6. The combined disk image with improved pixel sampling is shown in Figure 3. Disk rotation is clearly detected as a velocity offset between the southern and northern disks, approaching and receding from us, respectively. HD 141569 A has its eastern disk near to us known from the asymmetric azimuthal illumination of the disk, which is attributed to the forward scattering of the grains (Weinberger et al. 1999). The disk rotation is therefore clockwise in projection on the sky, which is consistent with the winding of the spiral arms at 200–400 AU of the star (Clampin et al. 2003). A simple geometrical model is calculated for an infinitely thin disk vignetted by the slit field-of-view with the gas in the disk in the Keplerian rotation until the inner truncation ($M_* = 2.0 M_\odot$, Marín et al. 2004; inclination angle $\phi = 51°$ from face-on, Weinberger et al. 1999). The velocity dispersion along the line of sights well agrees with the observed disk image in the line emission, and the lack of high velocity component close to the central star manifests the innermost part of the disk is indeed evacuated (Figure 3).

4. Discussion

The size of the central cavity gives some insights into its formation mechanism. The inner clearing is apparently larger than the magnetospheric truncation ($r \sim R_* \sim 0.01$ AU), or the dust sublimation radius ($r \sim 0.1$ AU), therefore those mechanisms are not likely responsible. The cavity size is comparable to the gravitational radius of the star where the sound speed in the ionized medium is equal to the escape velocity of the system ($r_g = GM_*/c_i^2$; Shu et al. 1993, Hollenbach et al. 1994; ≈18 AU for $M_* = 2.0\ M_\odot$). The gravitational radius defines the innermost radius of a disk where the gas is driven away from the system once ionized by the stellar radiation. The rough agreement of the inner edge of the disk around HD 141569 A with the gravitational radius of the star indicates the cavity is being cleared by the photoevaporation working in combination with the viscous accretion.

The dissipation of an inner circumstellar disk is controlled by the two processes: the mass loss by photoevaporation and the viscous accretion on to the star. The viscous accretion is the primary drive to remove a disk, transporting bulk of the outer disk material inward eventually onto the star. On the other hand, the photoevaporation is a slow process, steadily removing a disk outside the gravitational radius as long as the extreme ultraviolet irradiation (EUV; $h\nu > 13.6$ eV) maintains. However, the persistency or EUV radiation, or, the origin of the ionizing photon is unclear, whether it is a consequence of active accretion (Muzerolle, Calvet, & Hartmann 2001; Muzerolle et al. 2004), or of the stellar activity (e.g. Deleuil et al. 2005). In the former case, the photoevaporation is expected to drop off as the viscous accretion slows down, which causes problem to disperse a disk within 10^7 yrs (Matsuyama, Johnstone, & Hartmann 2003; Ruden 2004). Although the photoionizing radiation is likely chromospheric, and holds until the end of the disk evolution in low-mass stars (Alexander et al. 2005); it may not directly apply to Herbig Ae/Be stars (Grady et al. 2005). The mass loss via photoevaporation proceeds most effectively immediate outside of r_g, as the disk wind decreases with the radius as $\dot{\Sigma}(r) \propto r^{-5/2}$ (Hollenbach et al. 1994). During the early phase of the disk evolution, the photoevaporation is relatively unimportant, as the viscous accretion quickly fills in the mass loss at the gravitational radius. However, as the disk declines, the viscous accretion slows down, and is eventually balanced by the photoevaporation. The net inflow across the gravitational radius is quenched, as the photoevaporation virtually reverses it. Starved for the further supply, the material inside r_g is quickly drained onto the star on the time scale of viscous evolution. In consequence, a disk dissipates on two distinct time scales (Hollenbach, Yorke, & Johnstone 2000; Clarke, Gendrin, & Sotomayor 2001; Armitage, Clarke, & Palla 2003; Matsuyama, Johnstone, & Hartmann 2003; Johnston et al. 2004; Takeuchi, Clarke, & Lin 2005; Alexander et al. 2006): the whole disk lifetime may last as long as $\sim 10^7$ yrs, while the evacuation of the inner disk is almost an instant ($\Delta t \sim 10^5$ yrs).

The presence of the central cavity clears several issues how the inner disk is removed at the end of the disk dissipation. The photoevaporation and the viscous accretion is likely effective to remove a inner disk, inside outward, without calling for any hypothetical planets to sweep it up. The radius of the inner clearing measures $r_i = 11$ AU, slightly smaller than the nominal gravitational radius of $r_g = 18$ AU. The smaller inner radius is in fact preferred by the latest models that incorporate far ultraviolet radiation (FUV; 6 eV$< h\nu <$13.6 eV) that thermally heats up the gas in the disk (Dullemond et al. 2006 for review). The mass loss by photoevaporation formulated by Shu et al. (1993) and Hollenbach et al. (1994) is actually the photoionization that assumes dissipation of the gas ionized by EUV. Adams et al. (2004) found FUV irradiation has significant contribution to disk wind; and it could launch as close as 0.2–0.5 r_g of the central star, when the pressure gradient at the central region is taken into account (Liffman 2003; Font et al. 2004). The location of the inner-rim of HD 141569 A better matches the new pictures.

HD 141569 is a triple system with low-mass companions B and C at 9″ away. The coeval formation of the system sets a robust age of 5±3 Myr (Weinberger et al. 2000), which agrees well with 4.7 Myr given by the full spectral modeling with the photometric analysis of the primary (Marín et al. 2004). The age of HD 141569 A sets a challenging time scale to form gas-giant planets inside the gravitational radius of the Herbig Ae star. The conventional model of gas-giant formation takes 1–10 Myr to form a Jupiter-like planet by accretion of gas onto a rocky core (Pollack et al. 1996; Hubickyj, Bodenheimer, & Lissauer 2005), which is uncomfortably close to the standard disk lifetime (∼3 Myr for the median disk lifetime, Haisch et al. 2001; Hillenbrand 2005 for review), although many ideas have been proposed to accelerate the core growth process (Inaba, Wetherill, & Ikoma 2003; Alibert et. al 2005; Kley & Dirksen 2005; Klahr & Bodenheimer 2006). The age of HD 141569 A suggests that giant planets may not have enough time to fully deplete the protoplanetary disk onto themselves, but likely have to compete with disks in dissipation. The subtlety in the disk dissipation and the planet forming time scale may explain a large scatter of disk fraction in a single age bracket of stars (e.g. Rieke et al. 2005), and eventually the diversity of the exoplanetary systems discovered to date (e.g. Marcy et al. 2005).

It is tempting to speculate on the origin of the isotope anomaly in the solar system in connection with the present observation. The dissociation time scale of CO in the normal interstellar medium is on the order of 10^2 yrs ($k_{\rm CO} \sim 2 \times 10^{-10}$ s^{-1}; van Dishoeck 1988), the molecule in the disk of HD 141569 A will be quickly destroyed without a shielding to the dissociating irradiation from the star ($\lambda <$ 1100 Å; van Dishoeck & Black 1988). The dust extinction could dilute the radiation (Kamp & Bertoldi 2000), however, the extinction cannot be too large, since the emission we observed here is the transition from the vibrationally excited state ($v = 2 - 1$), which needs UV photons to get pumped up ($\lambda <$1600 Å; Krotkov et al. 1980). The margin is not too wide. The extinction dilemma could be evaded by the line shielding either by molecular hydrogen, or by CO itself (van Dichoeck & Black 1988). In contrast to the dust extinction that dilutes UV radiation as a continuum, line shielding blocks the dissociative irradiation selectively. Self-shielding is only effective where the dust extinction is less than $A_V = 1$, but the CO is already optically thick. It is not clear if any of these conditions are met in HD 141569 A. The absence of near-infrared excess (Sylvester et al. 1996) only gives loose constraint, being consistent with the inner-rim as close as 0.24 AU of the star (Marín et al. 2004); although the coronagraphic and mid-infrared imaging suggests dust opacity drops at 30–160 AU and inward (Weinberger et al. 1999; Marsh et al. 2002). The column density of CO in the infrared emission ($N_{\rm CO} \sim 10^{11}$ cm^{-2}; Brittain et al. 2003) is too short to make self-shielding effective (Lee et al. 1996), however, the emitting CO does not necessarily properly represents the column density of shielding gas along the line of sight to the UV source.

With all these uncertainties, if self line-shielding is still at work, it may have an implication to the isotope anomaly imprinted in the early solar nebula. The correlated isotope fractionation in ^{17}O and ^{18}O in the primordial meteorites was once attributed to a supernova outburst occurred near the solar system at its infancy (Clayton 1993). Since then, numbers of accounts are proposed; injection of nucleosynthesized material by evolved stars (Busso, Gallino, & Wasserburg 2003), direct bombardment of high energy particles (Aléon et al. 2005), and isotope fractionation by self-shielding of CO (Clayton 2002). When the self-shielding operates, CO is fractionated to C^{16}O as the rare isotopomers C^{17}O and C^{18}O are readily destroyed for their lower opacity, leaving more ^{17}O and ^{18}O in atomic phase. The isotope enrichment in the atomic gas potentially explains the anomalous isotope ratio in the present solar system (Yurimoto & Kuramoto 2004; Lyons & Young 2005). Our observation found CO $v = 2 - 1$ emission at the inner-edge of the disk from the star, presumable planet forming distance. We might be witnessing the ongoing isotope fractionation similar to that might happen in the early history of our solar system.

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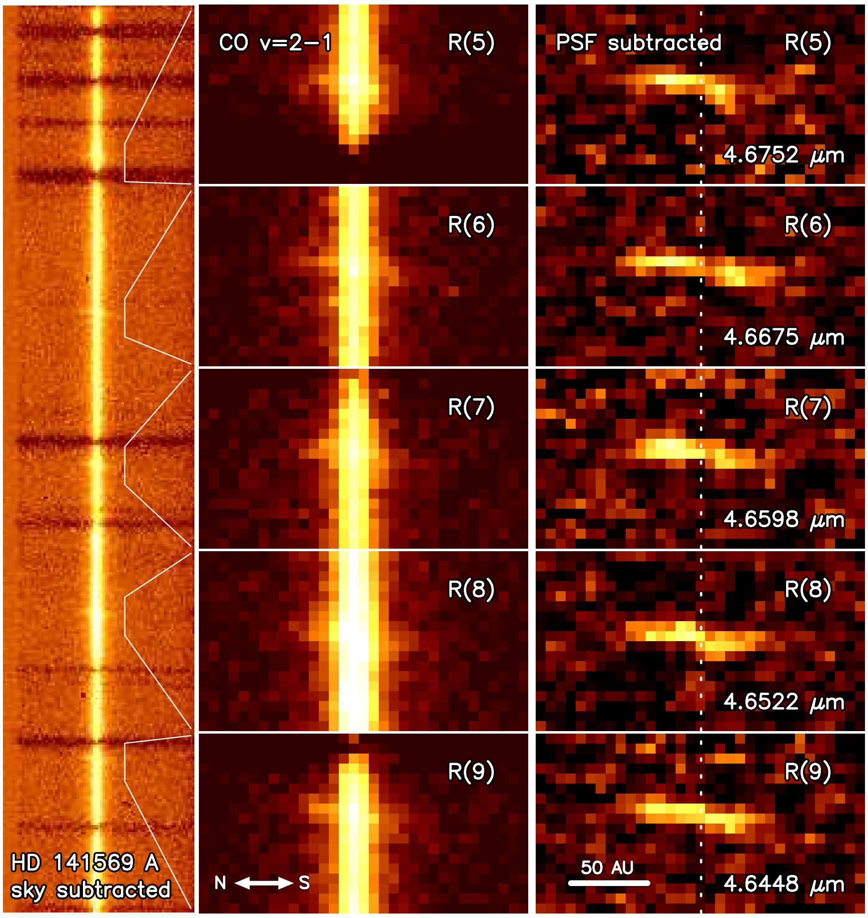

Fig. 1.— Left: a cut-out of the spectrogram of HD 141569 A at 4.6 μm obtained with IRCS at the Subaru Telescope on the night of 25th May 2005. The slit was oriented from north to south along the major axis of the disk projected on the sky, with north being the left hand side. The spatial and spectral distortion was corrected using emission lines in the telluric atmosphere. The emission lines of CO $v = 2 - 1$ within our spectral coverage are all found spatially extended up to 50 AU at both sides of the star. Middle column: the blow-up of the emission lines from $R(5)$ to $R(9)$. Right column: same as in the middle panels, but after one-dimensional point spread functions have been subtracted. The centrer of the PSF, therefore, the position of the star is marked by dotted verticals. Disk rotation is clearly visible, with the northern disk receding from us. The rotation is consistent with the spiral arms seen in the dust scattering (Clampin et al. 2003), and the earlier radio spectroscopy (Dutrey et al. 2004; Figure 3 presented in their paper accidentally shows the northern component of the CO emission is approaching toward us. The confusion has been cleared by private communication with A. Dutrey and J.-C. Augereau).

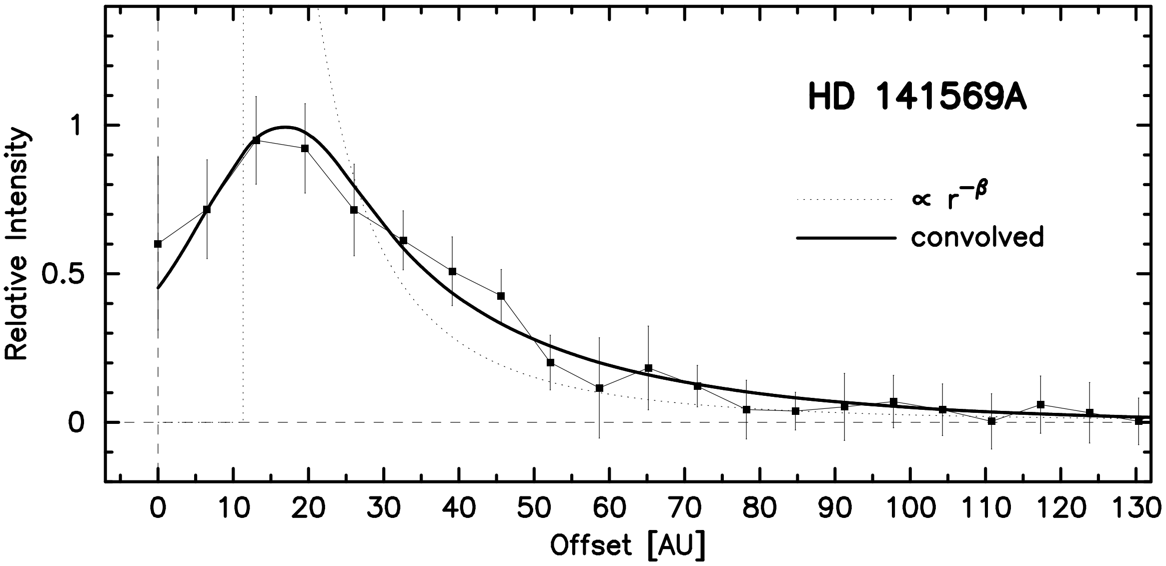

Fig. 2.— The radial profile of CO line emission at the central part of the disk. A power-law radial profile (dotted line) was fit to the observation after convolved with the PSF (solid line) to find the best-fit cut-off radius at $r_i = 11 \pm 2$ AU. The error bars (1 σ) are given by the standard deviation of the radial profiles extracted from CO $v = 2 - 1$ $R(5)$ to $R(9)$.

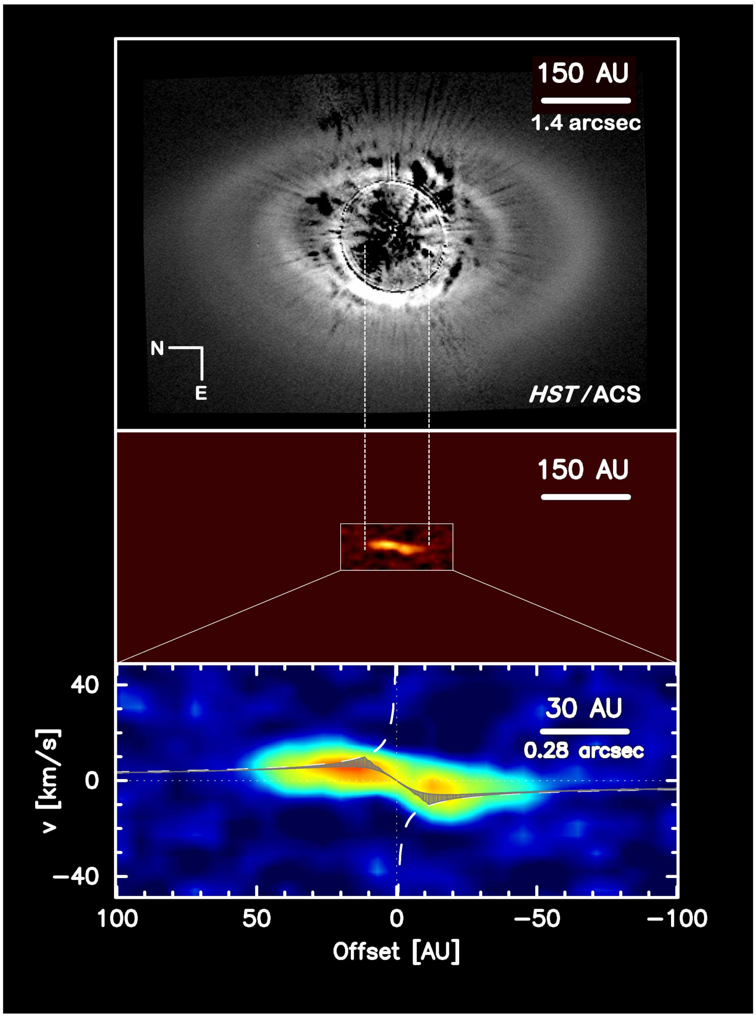

Fig. 3.— Top: *HST*/ACS image of the debris disk around HD 141569 A from Clampin et al. 2003 at visible wavelength (λ =606 nm). The central 100 AU are masked by the coronagraph. Middle: the image of the composite line emission from CO $v = 2 - 1$ $R(5)$–$R(9)$. Only those lines less severly overlapped with the telluric absorption lines were used. The north is left, and the wavelength increases to the top. Bottom: the close-up view of the middle panel. The gap between the northern and the southern disks is clearly resolved. The velocity dispersion along the line of sight is calculated for a disk with an inner hole of 11 AU with the gas inside the disk in the Keplerian rotation (for assumed central mass of 2.0 $M_\odot$ with the inclination angle ϕ =51°). The velocity contour overlaid in the shade is consistent with the observed line image. The rotation curve in the case of no truncation at the inner disk is shown in the dashed line. The lack of high velocity component close to the star represents that the molecular gas is cleared up already at the central part of the disk.