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AN EVOLVED DISK SURROUNDING THE MASSIVE MAIN-SEQUENCE STAR MWC 297?

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ABSTRACT

We present the results of the interferometric observations of the circumstellar disk surrounding MWC 297 in the continuum at 230 GHz (1.3 mm) and in the ($J = 2$–1) rotational transitions of ^{12}CO,^{13}CO, and C^{18}O using the Submillimeter Array. At a distance of 250 pc, MWC 297 is one of the closest, young massive stars ($M_* \sim 10\ M_\odot$) to us. Compact continuum emission is detected toward MWC 297 from which we estimate a disk mass (gas+dust) of 0.07 $M_\odot$ and a disk radius of ≤80 AU. Our result demonstrates that circumstellar disks can survive around massive stars well into their main-sequence phase even after they have become optically visible. Complementing our observations with the data compiled from the literature, we find the submillimeter dust opacity index β to be between 0.1 and 0.3. If the emission is optically thin, the low value of β indicates the presence of relatively large grains in the disk, possibly because of grain growth. We do not detect any CO emission associated with the continuum source. We argue that the ^{13}CO emission from the disk is likely optically thin, in which case we derive an upper limit to the gas mass that implies significant depletion of molecular gas in the disk. The mass of this disk and the evolutionary trends observed are similar to those found for intermediate-mass Herbig Ae stars and low-mass T Tauri stars.

Subject headings: circumstellar matter — planetary systems: protoplanetary disks — stars: early-type — stars: emission-line, Be — stars: individual (MWC 297)

1. INTRODUCTION

There is now a growing body of evidence that indicates that the formation of massive stars (8–20 $M_\odot$) is mediated by disk accretion. Observational studies of massive protostellar objects in the submillimeter/millimeter continuum and molecular lines have revealed flattened disklike structures and outflows perpendicular to them, suggesting that massive stars of early B or perhaps even late O spectral types are born with disks (e.g., Zhang 2005; Cesaroni et al. 2007). If the high-mass stars are indeed born with disks, how long do these disks last around them? Do they survive long enough so that planet formation processes can proceed in them as is observed in the disks surrounding low- and intermediate-mass stars?

Since the Kelvin-Helmholtz contraction timescale for stars more massive than ~8 $M_\odot$ is shorter than both the free-fall and the accretion timescale (typically ~10^5 yr), they arrive on the zero-age main sequence (ZAMS) still embedded within their natal cores and accreting from the surrounding circumstellar disk (e.g., McKee & Tan 2003). Young high-mass stars accrete a significant amount of mass while on the ZAMS, even when surrounded by compact H II regions (Keto 2002; Sollins et al. 2005). The intense UV radiation from the central star eventually clears away the overlying envelope, and the star surrounded by a disk becomes visible in the optical/near-IR wavelengths. Residual accretion from the surrounding disk onto the central star may persist in these objects. A few such stars (spectral type B5 or earlier) have been known (e.g., Herbig Be stars) to show classical spectroscopic signatures of ongoing accretion and excess continuum emission longward of 2 μm, indicating the presence of circumstellar dust around them, presumably distributed in the surrounding disks (e.g., Natta et al. 2000; Manoj et al. 2006). Direct imaging studies at high angular resolution with interferometers have so far detected compact continuum emission around two such objects, viz., MWC 1080 and R Mon, and evidence for Keplerian rotation in the optically thick CO line emission from R Mon (Fuente et al. 2003, 2006). However, because of the large distances to these stars (≥800 pc), even with the high angular resolutions provided by interferometers, it is not easy to distinguish between flattened structures of a few thousand AU and bona fide circumstellar disks.

In this Letter, we present the first interferometric observations of MWC 297, which is a young 10 $M_\odot$ main-sequence star of spectral type B1.5 (Drew et al. 1997). Although distances of 450–870 pc to MWC 297 have been cited in the literature (e.g., Canto et al. 1984), the more reliable distance estimate based on a detailed study of the stellar properties and line-of-sight extinction by Drew et al. (1997) places it at a distance of 250 ± 50 pc. MWC 297, thus, is one of the closest, young massive stars to us and is an ideal candidate for high-resolution studies.

2. OBSERVATIONS AND DATA REDUCTION

MWC 297 was observed with the Submillimeter Array[6] (SMA; Ho et al. 2004) in the continuum at 230 GHz (1.3 mm) on 2006 August 28. The two sidebands, each of 2 GHz bandwidth, include the rotational transitions ($J = 2$–1) of ^{12}CO,^{13}CO, and C^{18}O, and the correlator was configured to provide a velocity resolution of 0.5 km s^{-1} for the CO(2–1) line, which was centered in the upper sideband. The observations were made in the compact array configuration of the SMA, where the projected shortest and longest baselines were ~14 and ~69 m (10 and 53 kλ), respectively.

We used Uranus for both bandpass calibration and flux calibration. Amplitude and phase calibrations were done with the

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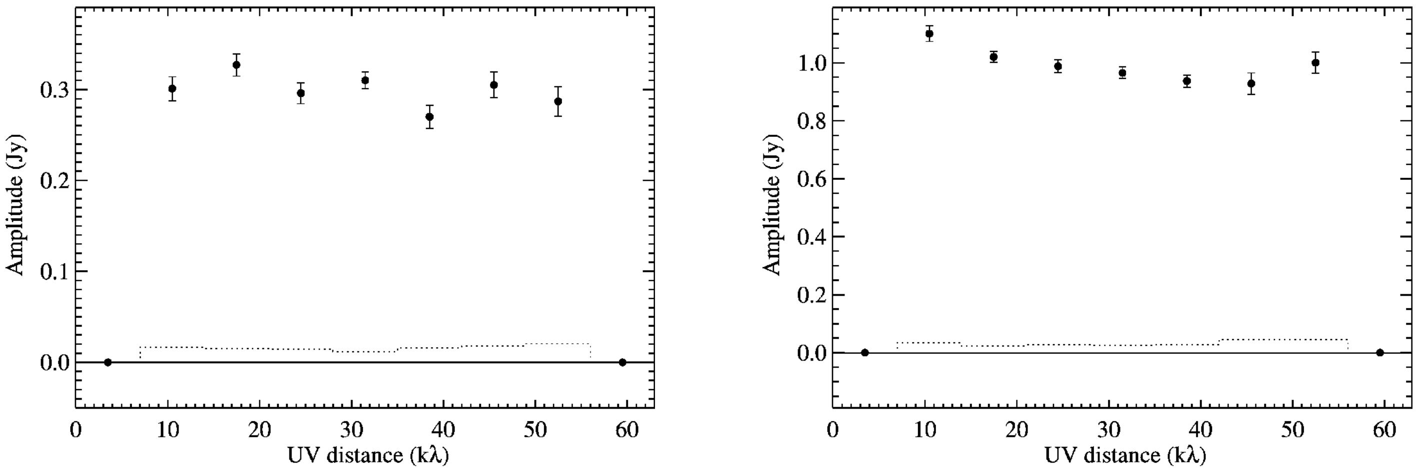

FIG. 1.—Visibility amplitudes averaged vectorially in annular bins with respect to the observed 1.3 mm continuum peak plotted against the *uv* distance for MWC 297 (*left*) and for the quasar 1743−038 (*right*). Error bars plotted are 1 σ errors in amplitude. The dotted lines indicate expected amplitude for zero signal.

quasar 1751+096, and the quasar 1743−038 was observed to verify the quality of phase referencing from 1751+096. The visibility data were calibrated using the MIR package, and the maps were generated and CLEANed using the NRAO AIPS package. Even after calibration, the continuum visibility data of the reference quasar 1743−038 showed evidence for phase decorrelation at longer baselines. The degree of decorrelation was similar for 1743−038 and MWC 297. We self-calibrated the visibility data for both 1743−038 and MWC 297 at a time interval of 4 minutes, which significantly reduced the phase decorrelation. The vector averaged visibility amplitude plotted against the *uv* distance for MWC 297 and the quasar 1743−038 after self-calibration is shown in Figure 1. We imaged the self-calibrated continuum visibilities of MWC 297. The resultant size of the synthesized beam was 3.11″ × 2.97″ with uniform weighting (P.A. ∼ 45°). The contour map of the observed continuum emission at 1.3 mm is shown in Figure 2. We expect the maximum uncertainty in source positions to be ≲0.3″ on the basis of the positions of quasars mapped in our SMA observations. Uncertainties in the absolute flux are estimated to be 20%.

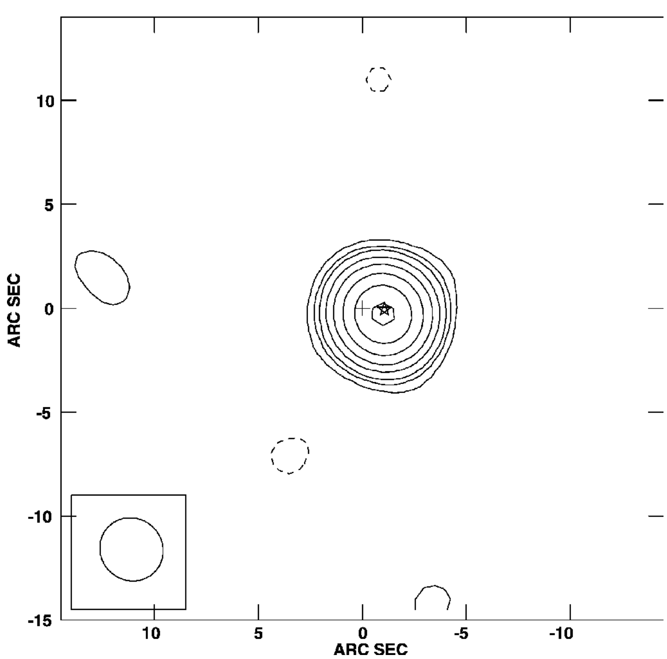

FIG. 2.—Contour plot of 1.3 mm continuum emission observed toward MWC 297. The cross corresponds to the phase center ($18^h27^m39.600^s$, −03°49′52.00″ [J2000.0]), and the star symbol denotes the stellar position from 2MASS. The boxed ellipse in the lower left corner indicates the position angle and FWHM of the synthesized beam. The contours begin at ±3 σ (where σ = 2 mJy beam^{-1}) and increase in steps of $\sqrt{3}$.

3. RESULTS

Compact continuum emission with a total measured flux density of 300 mJy is detected toward MWC 297 at 1.3 mm. The angular separation between the 1.3 mm continuum peak and the stellar position is less than 0.3″. Therefore, we assume that the compact continuum source is centered on the star. A two-dimensional Gaussian fit to the continuum map of MWC 297 yields an observed size of 3.14″ × 3.02″ and a deconvolved size of $0.64^{+0.10}_{-0.64}$ arcsec × $0.11^{+0.60}_{-0.11}$ arcsec at P.A. = 165° ± 15°. Allowing for the possibility of the phase decorrelation in our observations affecting the observed size, we take the longer dimension of the deconvolved size as an upper limit to the source size. At the distance of MWC 297, it gives a source radius of 80 AU.

MWC 297 is known to have an ionized wind associated with it (Malbet et al. 2007; Drew et al. 1997). The flux densities at 3.6 and 6 cm, measured toward MWC 297 with the Very Large Array (Skinner et al. 1993), give a spectral index of 0.6 ($F_\nu \propto \nu^{0.6}$), appropriate for free-free emission from an optically thick, ionized wind. Assuming that this emission continues to the millimeter wavelengths with the same spectral index, we subtracted the possible contribution due to the free-free emission from the total observed flux at 1.3 mm and obtained a flux density of 200 mJy as due to dust emission.

If the dust emission is optically thin at millimeter wavelengths, assuming a gas-to-dust mass ratio of 100 and a dust opacity per unit mass of dust plus gas $\kappa_\nu = 0.005\ [\nu(\mathrm{GHz})/230.6]^\beta\ \mathrm{cm^2\ g^{-1}}$ (Cesaroni et al. 2007; Kramer et al. 1998), we obtain a total mass of 0.07 $M_\odot$ for the circumstellar material (gas+dust) associated with MWC 297. A dust temperature of 100 K is assumed in this calculation. From the mass and the upper limit to the source radius, we computed the optical extinctions along the line of sight through the continuum source to the central star to probe the geometry of the circumstellar material. If the circumstellar material is distributed in a spherical envelope of uniform density, the optical *V*-band extinction would be ≳10^4 mag. However, the observed extinction A_V is only 8 mag (Drew et al. 1997). This strongly suggests that the circumstellar dust is likely distributed in a comparatively flattened and inclined morphology around MWC 297, perhaps in the form of a disk.

In Figure 3, we present the spectral energy distribution (SED) of MWC 297 at submillimeter, millimeter, and centimeter wavelengths. We fit the observed points with a combination of free-free emission arising in an ionized wind and optically thin dust emission from a circumstellar disk of mass 0.07 $M_{\odot}$. The best fit is obtained when the dust opacity power-law exponent β has a value between 0.1 and 0.3. This is much lower than that observed for interstellar grains ($\beta = 2$) and the representative value used for circumstellar disks ($\beta = 1$). The low value of β is often interpreted as arising due to the average size of the emitting dust grains being relatively larger. Larger grain size in the circumstellar environment around MWC 297 has also been reported independently from studies on the wavelength dependence of extinction toward the star at the optical wavelengths (Gorti & Bhatt 1993). This argues for possible grain growth in the optically thin circumstellar material around MWC 297.

In order to construct the SED and to determine the value of β, we have used large-beam (~20″) single-dish measurements at submillimeter wavelengths with the James Clerk Maxwell Telescope (JCMT) in conjunction with our interferometric data point at 1.3 mm. The single-dish measurements are likely to have contribution from nearby extended structures. However, major contribution to the single-dish measurements still comes from the compact continuum source that we detect with the SMA, and therefore, the derived value of β should not be significantly affected. For instance, at 1.3 mm, 60% of the dust emission observed with the 19″ beam of the JCMT (Mannings 1994) and 74% of the dust emission observed with the 11″ beam of the IRAM (Henning et al. 1998) comes from the compact continuum source of ~0.6″ in size. Assuming that the relative contribution from extended emission to the total dust emission measured with JCMT is the same in all other submillimeter wavelengths and performing a similar fit yields $\beta \lesssim 0.1$. Thus, the value of β that we derive can safely be treated as an upper limit.

However, we note here that low value of β is also consistent with emission from an optically thick disk. If the 1.3 mm continuum dust emission is optically thick, then the measured flux density implies a disk radius of only ~28 AU. In order to have the optical depth $\tau_{1.3\,\mathrm{mm}} \geq 1$, such a disk should have a mass $M_{\mathrm{disk}} \geq 0.06\ M_{\odot}$.

We do not detect any CO(2–1) or ^{13}CO(2–1) emission with the SMA at any V_{LSR} at the position of the continuum source associated with MWC 297. The line-of-sight extinction of $A_V \sim 8$ mag toward MWC 297 corresponds to CO(2–1) and ^{13}CO(2–1) column densities of about 9×10^{17} cm^{-2} and 1.5×10^{16} cm^{-2}, respectively (Frerking et al. 1982), with an assumed [^{12}CO]/[^{13}CO] elemental isotope ratio of 60. The optical depths of CO(2–1) and ^{13}CO(2–1) will be $300/\Delta v$ (km s^{-1}) and $5/\Delta v$ (km s^{-1}), respectively. The CO(2–1) emission that we observe toward MWC 297 with the 10 m Submillimeter Telescope (SMT) at ARO is extended and has a velocity width of ~10 km s^{-1} (to be published elsewhere). The optically thick, extended foreground CO cloud is resolved out by the SMA in our observations. The ^{13}CO(2–1) line has a line width of ~3 km s^{-1} (SMT observations, to be published elsewhere). The optical depth of the foreground ^{13}CO will be 1–2. If the ^{13}CO(2–1) line from the circumstellar disk of MWC 297 has a V_{LSR} and a Δv close to those of the foreground ^{13}CO, then most of the ^{13}CO(2–1) emission would have been absorbed by the foreground component. However, a Keplerian disk surrounding a central mass of 10 $M_{\odot}$ will have a rotational velocity of ~11 km s^{-1} at a radius of 80 AU. The ^{13}CO emission from such a rotating disk would show a line width reaching 22 km s^{-1}, and we should have detected the high-velocity component of the disk emission away from the foreground cloud velocity. Our channel maps (velocity resolution = 0.5 km s^{-1}) at various V_{LSR} in the ^{13}CO(2–1) line indicate no hint of a localized ^{13}CO emission at the position of the dust continuum at an rms noise level of 150 mJy beam^{-1}.

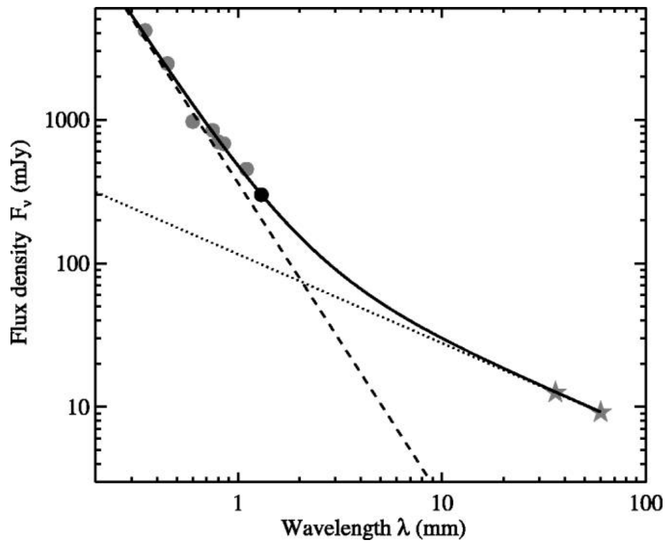

FIG. 3.—SED of MWC 297 at centimeter, millimeter, and submillimeter wavelengths. The flux densities at centimeter wavelengths (*gray star symbols*) are from Skinner et al. (1993) and at submillimeter wavelengths (*gray circles*) from Mannings (1994). The black circle is our observed point at 1.3 mm. The dotted line is the model prediction for the free-free emission component from an ionized wind with $\alpha = 0.6$. The dashed line is the best-fitting disk model with disk mass of 0.07 $M_{\odot}$ and $\beta = 0.2$. The solid line is the sum of both the components.

If the ^{13}CO emission from the disk is optically thick, our detection limit (53 mJy beam^{-1}/4 km s^{-1}) implies a source size smaller than the dust disk size. This is contrary to what is observed generally for circumstellar disks where the sizes of the gas disks are a factor of 2–3 times larger than the dust disks (e.g., Simon et al. 2000; Piétu et al. 2007). Moreover, the ^{12}CO/^{13}CO line ratios observed for circumstellar disks in general suggest ^{13}CO emission to be optically thin (e.g., Thi et al. 2001). Therefore, the ^{13}CO emission from the disk surrounding MWC 297 is likely to be optically thin, and from our sensitivity limit we obtain an upper limit on the gas mass. If the circumstellar material around MWC 297 is distributed in a Keplerian disk of radius 80 AU and assuming a gas excitation temperature of 50 K, [^{12}CO]/[^{13}CO] ratio of 60, and H_2/^{12}CO conversion factor of 10^4, the upper limit on the gas mass estimated from our detection limit for ^{13}CO(2–1) line emission is $3.5 \times 10^{-4}\ M_{\odot}$. This is about 200 times less than the disk mass estimated from dust continuum emission and implies a gas-to-dust mass ratio of ~0.5. Such discrepancies of about 2 orders of magnitude in the total masses derived from continuum and CO line measurements have been known for disks around T Tauri stars and Herbig Ae stars (e.g., Mannings & Sargent 1997; Thi et al. 2001). Suggested causes are gas dispersal in the disk, CO depletion due to freezing-out onto the grains, and photodissociation, or the line emission being partially optically thick (e.g., Thi et al. 2001; Dutrey et al. 1996). In the case of MWC 297, which is a hot, main-sequence star, gas dispersal and CO depletion due to photodissociation are likely to be important.

4. DISCUSSION

MWC 297 is a young, 10 $M_{\odot}$ main-sequence star that is already past the major accretion phase and has built up most of its mass. The star is optically visible, indicating that it has cleared most of the surrounding material. Our interferometric observations with the SMA show that it is still surrounded by a circumstellar disk of mass 0.07 $M_\odot$ and radius $\lesssim$80 AU. The disklike structures detected in high-mass ($M_* \sim 8$–20 $M_\odot$) protostars have masses in the range of 1–12 $M_\odot$ and radii $\geq$500 AU (Cesaroni et al. 2007; Zhang 2005 and references therein). The disk surrounding MWC 297, therefore, must be the remnant of a more massive disk of the earlier phase, and this supports the proposition that massive stars are formed via disk accretion. It also demonstrates that circumstellar disks can survive around massive stars well into their main-sequence phase even after they have become optically visible. Reported evidence for the existence of Keplerian disks surrounding 8–10 $M_\odot$ Herbig Be (HBe) stars also support this assertion (Fuente et al. 2006; Schreyer et al. 2006).

Other than MWC 297, compact dust continuum emission from the circumstellar disks surrounding optically visible early B-type stars (HBe stars) has been detected only around two B0 type stars, viz., MWC 1080 and R Mon. Based on the disk masses derived from these observations, it has been argued that the disk masses in HBe stars are at least an order of magnitude lower than that in intermediate-mass Herbig Ae stars and low-mass T Tauri stars (Fuente et al. 2003, 2006). However, because of the large distance to MWC 1080 (2200 pc; Natta et al. 2000; Manoj et al. 2006), the continuum emission detected at 2″ scale corresponds to a linear scale of ~4000 AU and therefore cannot be unambiguously considered as arising from a circumstellar disk. In the case of R Mon, which is at a distance of 800 pc, the continuum emission appears to come from a compact disk of radius 150 AU and mass 0.014 $M_\odot$ (Fuente et al. 2006). Thus, the disk masses estimated for early B-type stars are comparable to those found for Herbig Ae stars (Natta et al. 2000) and T Tauri stars (Andrews & Williams 2005), given the uncertainties in the mass estimates.

The disk surrounding MWC 297 shows evidence for some degree of physical evolution. If the emission at submillimeter and millimeter wavelengths is optically thin, then the low value of β that we derive implies that the circumstellar dust grains around MWC 297 have sizes larger than the interstellar grains. This indicates that the grain growth has possibly begun in the disk. Such grain growth has also been inferred for the disk surrounding R Mon (Fuente et al. 2006). We also find evidence for significant depletion of CO in the disk surrounding MWC 297. Interestingly, similar results indicating grain growth and depletion of molecular gas in the disks have been reported for low-mass T Tauri stars and intermediate-mass Herbig Ae stars (Andrews & Williams 2005; Acke et al. 2004; Thi et al. 2001). This would suggest that the disk evolution proceeds not very differently in the disks surrounding young massive stars from that observed for the disks in low-mass and intermediate-mass stars.

Although the depletion of molecular gas and grain growth in the disk seem to indicate that the disk surrounding MWC 297 is relatively evolved, the spectroscopic signatures like a variety of emission lines in the near-infrared, and the optical wavelengths show that it is driving a wind and is extremely active (e.g., Drew et al. 1997; Malbet et al. 2007). Malbet et al. (2007) have successfully modeled the emission lines as arising in a stellar wind with the high-velocity (600 km s^{-1}) Hα and Hβ emission originating from a large and somewhat spherical region, while the Brγ line is confined to a narrow region just above the disk where the velocity is dominated by the disk Keplerian rotation. However, what drives this wind is not very clear. Direct mass loss from the star and the standard classical Be wind models have been found to be unsuccessful in explaining the observed wind properties of MWC 297 (Malbet et al. 2007; Drew et al. 1997). The activity in MWC 297 must be related to the circumstellar disk surrounding it, and it is likely that the wind is accretion-driven. Although not very conclusive, spectroscopic evidence seem to suggest that residual accretion persists in the circumstellar disk surrounding MWC 297.

The disk that we detect around MWC 297 is possibly in an intermediate evolutionary stage between the more massive accretion disk and the debris disk. The primordial disk material has begun to evolve, and the disk is in the process of being dissipated. It is interesting to note that disks with similar observational characteristics in intermediate-mass and low-mass stars are generally thought to be the sites of planet formation. This opens up the intriguing possibility of planet formation in the disks surrounding massive stars. However, detailed studies of more such objects are needed to explore such a possibility.

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