THE MOLECULAR ACCRETION FLOW IN G10.6–0.4

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ABSTRACT

We have observed the ultracompact H II region G10.6–0.4 with the VLA in the 23 GHz continuum and the NH3 (3, 3) inversion line. By analyzing the optical depth of the line as well as the kinematics, we have detected a flattened, rotating molecular accretion flow. We detect the fact that the highest column density gas is more flattened, that is, distributed more narrowly, than the lower column density gas, and that there is some inclination of the rotation axis. The rotation is sub-Keplerian, and the molecular gas is not in a rotationally supported disk. We do not find a single massive (proto-)star forming in a scaled-up version of low-mass star formation. Instead, our observations suggest a different mode of clustered massive star formation, in which the accretion flow flattens but does not form an accretion disk. Moreover, in this mode of star formation the central object can be a group of massive stars rather than a single massive star.

Subject headings: accretion, accretion disks — H II regions — ISM: individual (G10.6–0.4) — stars: formation

1. INTRODUCTION

G10.6–0.4 is a bright, 2.5 Jy at 23 GHz (Keto et al. 1987a), ultracompact (UC) H II region (Wood & Churchwell 1989) at a distance of 6.0 kpc (Downes et al. 1980) in an area of active star formation. The associated Infrared Astronomical Satellite (IRAS) point source, IRAS 18075–1956, has a luminosity of 9.2 × 10⁵ L⊙ (Casoli et al. 1986) and has colors that meet the criteria of Wood & Churchwell (1989) for an UC H II region. G10.6 is known to be embedded in a hot molecular core (HMC: Braz & Epchtein 1983; Ho & Haschick 1986; Plume et al. 1992). The core is thought to contain 1200 M⊙ of gas within a radius of 0.2 pc, based on an analysis of a variety of dust continuum measurements (Mueller et al. 2002), and 3300 M⊙ within 1.1 pc, based on C18O and C17O measurements (Hofner et al. 2000). Previous studies of the inversion lines of NH3 have determined that the molecular core is rotating and collapsing inward toward the UC H II region (Ho & Haschick 1986; Keto et al. 1987b, 1988; Keto 1990). In these studies, using the NH3 (1, 1) and NH3 (3, 3) lines, rotation is seen at size scales from 1 pc down to 0.08 pc, and infall is detected in the form of redshifted absorption seen against the continuum source. CH3OH and H2O masers are seen and infall is detected in the form of redshifted absorption seen against the continuum source. CH3OH and H2O masers are seen distributed linearly in the plane of the rotation (Walsh et al. 1998; Hofner & Churchwell 1996), while OH masers seem to lie along the axis of rotation (Argon et al. 2000). In C18O (J = 1 → 0), Ho et al. (1994) see 10³ M⊙ of dense (n ~ 10⁶ cm⁻³), rotating gas in a flattened (0.3 × 0.1 pc), disklike structure. At the highest resolution achieved in earlier work, infall and rotation in the molecular gas were seen simultaneously in absorption, showing that the molecular gas was spiraling inward on size scales comparable to the size of the UC H II region.

Recent observations of G10.6 hinted that it might represent a previously unobserved mode of high-mass star formation. Observations of H66α from the ionized gas within the UC H II region indicate that the ionized gas is also spiraling inward toward the stars at the center of the UC H II region (Keto 2002a). Subsequent theoretical work showed that in small H II regions, the gravitational effect of the central star(s) can overcome the thermal pressure of the ionized gas, causing the molecular accretion flow to pass through the H II region boundary and continue inward as an ionized accretion flow (Keto 2002b). In this model, the H II region boundary exists as a standing R-type ionization front within a continuous accretion flow. These results differ from classical treatments of the pressure-driven expansion of H II regions, which predict outward motion of the ionized gas as soon as the H II region is formed (Strömgren 1939; Spitzer 1978). In the classical model for pressure-driven expansion, the H II region boundary, after a very short phase as a moving R-type front, will develop a characteristic double-front structure composed of an isothermal shock followed by a moving D-type ionization front. As the H II region expands, most of the displaced molecular material remains between the shock and the ionization front as a dense, outward-moving shell, which snowplows ahead of the H II region. If, however, the accretion flow passes through a standing R-type ionization front at the H II region boundary and continues toward the star(s) as an ionized flow, as suggested by Keto (2002b), there will be no dense molecular layer at the boundary, and all the molecular gas will be moving inward.

Sollins et al. (2005) did preliminary analysis of the data presented here and showed that G10.6 is accreting through its UC H II region. The velocities of the molecular gas showed clear evidence of both infall and rotation. Based on geometric arguments, Sollins et al. (2005) concluded that the infalling layer proceeded directly up to the ionization front. They also showed a nondetection of any expanding molecular gas. The nondetection placed such a stringent upper limit on the mass of any expanding molecular shell that might be present, that it was concluded that no such expansion was taking place, and that the accretion in the ionized and molecular gas were all part of a single accretion flow that continues across a stalled ionization front.

In this paper we present a more detailed analysis of the NH3 data. We conclude that, while the accretion flow is spherical at large radii, the rotation does cause it to flatten somewhat on the size scale of the UC H II region, so that the highest column densities appear in a thin strip. We also conclude that the axis of rotation is inclined away from the observer in the northeast. We find that G10.6 is quite different than other young high-mass stars in which disklike molecular structures have been observed (Zhang et al. 1998, 2002; Shepherd & Kurtz 1999; Chini et al. 2004).

2. OBSERVATIONS

We observed the UC H II region G10.6 with the NRAO Very Large Array (VLA)² on 2002 February 1, with the phase center

² The National Radio Astronomy Observatory is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.
at \( \alpha(J2000.0) = 18^h10^m28^s683, \delta(J2000.0) = -19^\circ55'49''07'\). We observed the (3, 3) inversion line of \( \text{NH}_3 \) at 23.870130 GHz with 63 spectral channels of width 48.828 kHz (0.61 \( \text{km s}^{-1} \)) for a total bandwidth of 3.125 MHz (38.7 \( \text{km s}^{-1} \)) centered on \( v_{\text{LSR}} = 10 \text{ km s}^{-1} \), and the 1.3 cm continuum with a bandwidth of 15.6 MHz. The array was in the A configuration, yielding a uniform-weighted synthesized beam of width 0\('\!0.12 \times 0.072 \text{pc} \) for a physical resolution of 0.0034 \( \times 0.0021 \text{AU} \) or 700 \( \times 430 \text{AU} \).

We observed the quasars 3C 286, 3C 273, and 1733—130 for flux, bandpass, and phase calibration respectively. Self-calibration of the source amplitudes and phases resulted in a noise level of 0.18 (0.14) mJy beam\(^{-1} \) in the uniform- (natural) weighted continuum map, and 1.9 (1.5) mJy beam\(^{-1} \) in each uniform- (natural) weighted channel map, about 3 times the thermal noise limit. The images were deconvolved by CLEANing in the usual way with the AIPS task IMAGR. No special steps were taken to deal with the fact that the emission area is much larger than the synthesized beam. The total flux in the resulting natural-weighted continuum map is 2.5 Jy, which is consistent with the total flux detected in earlier lower resolution maps of 23 GHz continuum (Keto et al. 1987b). For this reason, we believe that the continuum map is missing very little flux due to the lack of short baselines.

Expressed as a temperature, our sensitivity in a natural-weighted continuum map is about 25 K and in a natural-weighted channel map is about 280 K. The physical temperature of the molecular gas around G10.6 is estimated to be only 110 K at the ionization front (Keto 1990). Thermal line emission always has a brightness temperature less than the temperature of the gas. Thus, the brightness possible thermal emission from the molecular gas would be undetectable, less than 0.4 \( \sigma \). Absorption, however, should be detectable at a wide range of optical depths. The continuum has a peak brightness temperature of 6900 K, and since the noise level is a channel map is 280 K, the molecular line absorption should be detectable at up to 25 \( \sigma \). The quality of the self-calibration solutions and improvements in the K-band receiver system at the VLA have resulted in 25 times better sensitivity in our \( \text{NH}_3 \) (3, 3) channel maps than in the previous best existing \( \text{NH}_3 \) (3, 3) data for this source (Keto et al. 1988), with 3 times better spatial resolution and 2 times better velocity resolution. A sample spectrum is shown in Figure 1.

It should be noted that we have achieved the highest possible angular resolution in studying the problem of high-mass star formation. With the VLA in its most extended array configuration, at a frequency of 23 GHz, our spatial resolution is 0\('\!0.1 \text{AU} \). Imaging thermal (i.e., nonmasing) molecular gas at that resolution is only possible toward sources with strong continuum emission, and only at wavelengths that include spectral lines useful for studying the dense gas surrounding UC H \( \Pi \) regions. Using radiation with wavelengths around a centimeter is ideal because it is near the peak of the continuum emission from many interesting UC H \( \Pi \) regions. At lower frequency, the spatial resolution decreases. At higher frequency the brightness temperature of the continuum emission declines rapidly. So for optimal backlighting from the UC H \( \Pi \) region, centimeter wavelengths are ideal. There are few thermal lines associated with high-density gas in the centimeter wavelength regime apart from the inversion lines of ammonia, which have a critical density of roughly \( 10^4 \text{ cm}^{-3} \) (Ho & Townes 1983). In addition to its fortuitous wavelength, the hyperfine structure (one main line, four satellite lines) of the ammonia inversion transitions is extremely useful. Because the different hyperfine components have well-known intrinsic line strengths, the ratio of the main line to a satellite line can be used to directly calculate the optical depth (what we call hyperfine optical depth) and column density of the ammonia in the rotational state in question, in this case \( (J, K) = (3, 3) \). While the optical depth of any absorption line can be calculated directly by comparing the depth of the absorption to the strength of the background continuum, this apparent optical depth has limitations. If the filling factor of the absorbing gas is less than 1, the apparent optical depth decreases. Moreover, for deeply embedded objects such as G10.6, the main hyperfine component easily saturates. For this reason, the satellite lines, which are much more optically thin and do not saturate easily, are invaluable in investigating the highest optical depths and column densities.

We report six key observational results. First, we find that the absorbing molecular gas is less spatially extensive than the continuum emission and, on average, northeast of the average position of the continuum emission. Second, we find that the highest column density gas is localized in clumps, while lower column density gas is seen over the entire face of the UC H \( \Pi \) region. Third, we find that the characteristic size scale of the infall and rotation kinematic pattern of the molecular gas is larger than the characteristic size scale of the structure in either the optical depth maps, or the continuum map. Fourth, we find that the highest optical depth gas is missing on the southwest side of the UC H \( \Pi \) region, reinforcing the idea that the absorption is preferentially located in the northeast. Fifth, on size scales smaller than the synthesized beam, i.e., less than 0\('\!0.1 \times 500 \text{AU} \), in more than 75\% of the pixels where absorption is detected, the filling factor of the absorbing gas is greater than 0.7. Sixth, none of the sharp edges clearly seen in the continuum emission are seen in maps of the optical depth.

We find that the absorbing molecular gas, as located by the actual line absorption, the apparent optical depth, and the hyperfine optical depth, is on average northeast of the continuum emission. The dotted lines show the continuum level, here 6700 K, the continuum \( \pm 3 \sigma \), and zero. The first satellite line is clearly visible, but the outer satellite is out of the spectral window.

3. RESULTS

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emission and is spatially narrower than the continuum emission in the direction of the minor axis, with the hyperfine optical depth being the most skewed to the northeast, and the most narrow. We have taken slices through the maps shown in Figure 2. The slices run northeast-southwest and are separated by a synthesized beam width (\(0''14\)). For each slice we have calculated the first moment to determine the mean position of the flux in the maps and the second moment to determine the width of the flux in the maps.

Figures 3 and 4 show the mean positions and widths as a function of position. The origin was chosen so that the mean positions in the continuum map have an average of zero. In the other three maps, the mean positions are generally northeast of the continuum positions. For the hyperfine optical depth map, the mean positions are on average \(0''07\) northeast of the continuum mean positions. Only in slices that pass through the large line width clump, noted in Figure 5, are the mean positions of the line absorption or...
apparent or hyperfine optical depth southwest of the continuum positions. The continuum is the widest of the three maps, while the hyperfine optical depth is the narrowest.

We find that the highest column density gas is localized in clumps, while lower column density gas obscures the entire UC H\textsc{ii} region. Comparing the two optical depth maps in Figure 2, we note that the hyperfine optical depth map looks "clumpier." The flux in the map is mostly collected into peaks about 0\,0\,25–0\,5 (1500–3000 AU) in size, while the apparent optical depth map shows more extended absorption over the whole face of the continuum source. The large line width clump at the western edge is visible in both maps, as is the clump at the eastern edge. Since the hyperfine optical depth is sensitive to much larger optical depths than the apparent optical depth, we interpret the difference in the maps to imply that, while there is an extended high-density envelope, the highest column densities are achieved only in highly localized areas.

We find that the characteristic size scale of the kinematic pattern is much larger than the characteristic size scales of fluctuations in the optical depth or continuum maps. Figure 5 shows the first and second moments of the line absorption in the main hyperfine component. Sollins et al. (2005) have interpreted the bull's-eye pattern in the first-moment map as showing simultaneous infall and rotation in a rotating, quasi-spherical, molecular accretion flow. The velocity field appears smooth across the absorption region, with the velocity gradient varying slowly. The size scale of this velocity pattern is visibly much larger than either the size of the continuum structures or the size of the clumpiness of the optical depth. The clumpiness in the optical depth seems to have no effect on the velocity pattern. The velocity pattern is established for the core as a whole, while the optical depth appears to be picking out overdensities that do not depart from the general flow. The map of the second moment shows that the line width is fairly constant across most of the face of the UC H\textsc{ii} region, at around 1.8\,km s\textsuperscript{-1} (FWHM ≈ 4.2\,km s\textsuperscript{-1}). One spot on the western edge of the UC H\textsc{ii} region shows a much larger width, >3\,km s\textsuperscript{-1} (FWHM > 7\,km s\textsuperscript{-1}). Interestingly, the bull's-eye pattern in the first-moment map shows no real effect of the anomalous large line width clump. That location does not stand out at all in the first-moment map, which means that the broadening at this point must be symmetric around a central velocity that fits with the overall velocity field.

The position-velocity cuts highlight both the kinematic pattern seen in the first moment and also the lack of high optical depth gas in the southwest of the UC H\textsc{ii} region. Figure 6 shows two position velocity cuts through the cube of apparent optical depths. The top panel shows a cut from northwest (negative
position) to southeast (positive position). The bottom panel shows a cut from southwest (negative position) to northeast (positive position). The largely spherical infall can be seen in the bottom panel as a backward V shape. Only the front side of the infall can be detected, since we are seeing the line in absorption. In the top panel, the backward V shape is seen again, but this time tilted, showing the effect of rotation. The bottom panel is a cut along the axis of rotation, so only infall is seen. The top panel is a cut in the plane rotation, so both infall and rotation are seen. In addition, it should be noted that the satellite line can be seen tracing all of the absorption in the top panel. The satellite appears everywhere in the plane of rotation. But in the bottom panel, the satellite fades out as the cut approaches the southwest side of the UC H II region. The satellite line has an intrinsic line strength of roughly 3% of the main line, so it traces only the highest optical depth gas. Thus, the highest optical depth gas is missing on the southwest side of the nebula.

The filling factor of the absorbing gas is large on size scales smaller than a synthesized beam, despite the apparent clumpiness in the optical depth maps. We have noted above that in many pixels, the main line saturates, i.e., in the central channels of the absorption line, there is no detectable flux. When absorbing gas has a nonzero filling factor, the ratio of the depth of the absorption to the continuum strength is related to the optical depth and the filling factor by

$$\frac{T_{\text{line}}}{T_{\text{cont}}} = \Phi(1 - e^{-\tau}) < \Phi,$$

where $T_{\text{line}}$ is the depth of the absorption, $T_{\text{cont}}$ is the strength of the continuum emission, $\Phi$ is the filling factor, and $\tau$ is the optical depth. It is impossible to tell the true optical depth when the line has saturated; only a lower limit can be determined. However, the above inequality shows that, no matter what the optical depth is, saturation is only possible where the filling factor is close to 1. Furthermore, every measurement of $T_{\text{line}}/T_{\text{cont}}$ puts a lower limit on $\Phi$. The lower limit on the filling factor is 0.7 in more than 75% of all the points in which main-line absorption is detected, and more than 0.9 in 55% of those points.

The sharp edges of the emission seen in the continuum map are absent in the optical depth maps. The V-shaped cavity on the northeast side of the UC H II region has very sharp edges, as does the spur to the south. These were interpreted as being the sides of an outflow cavity. The arcs of continuum emission to the east also have sharp edges on the sides facing the UC H II region. These arcs were interpreted by Sollins et al. (2005) as
ionized edges of clumps of molecular material. Photons leaking out of the central UC H II region could ionize these clumps externally, naturally creating the arcs, all of which have sharp edges pointing back toward the central source. By contrast, none of the structures in the molecular material have such sharp edges.

4. DISCUSSION

We draw two conclusions from the observational results. First, while the kinematics of the accretion flow are quasi-spherical with slow rotation, the density structure appears flattened and disklike. Second, the plane of the flattening is inclined to the line of sight.

4.1. The Molecular “Disk”

The densest part of the accretion flow is clearly flattened. The flattening is clear when one compares the apparent optical depth map to the map of the hyperfine optical depth. Figure 2 shows both maps. The hyperfine optical depth, which is sensitive to much higher column densities than the apparent optical depth, is distributed quite narrowly along a line perpendicular to the axis of rotation. Only the large line width clump in the west deviates from the midplane. We have calculated the width of the hyperfine optical depth and the apparent optical depth along 15 slices parallel to the axis of rotation (as described above). Figure 4 shows the widths perpendicular to the disk plane for each of the four maps: continuum, velocity-integrated absorption, apparent optical depth, and hyperfine optical depth. Again, the slices that include the large line width clump stand out. Otherwise, the velocity-integrated apparent optical depth, which is sensitive to lower column density gas, is distributed more broadly, while the velocity-integrated hyperfine optical depth, which is sensitive to much higher column densities, is narrower. The average second moment of the slices of the continuum...
map is 0.36, for the apparent optical depth map it is 0.23, and
for the hyperfine optical depth map it is 0.19. We conclude that
the highest density gas is collected in a flattened structure in the
midplane.

We make three specific predictions of what would be ob-
served if there were a geometrically thin, optically thick accre-
tion disk around G10.6, like those accretion disks seen around
low-mass stars. Imagine such a disk—UC H ii region system sche-
matically like the planet Saturn and its rings, with the equator in-
clined relative to the line of sight so that the south pole is visible.
(We discuss the inclination of the rotation axis in G10.6 below.)
The planet is the UC H ii region; the disk is the rings. The nor-
thern hemisphere is obscured by the rings, and the southern hemi-
sphere is not. There is a sharp edge to the obscuration, not a
gradual edge, where the planet emerges from behind the rings. In
the case of a thin-thick molecular disk around a UC H ii region,
we expect that the molecular absorption will be strong on one
side and much weaker on the other. Unlike the case of Saturn’s
rings, we do not expect the obscuration to be zero in the southern
hemisphere, where the disk is behind the UC H ii region, because
the whole object is embedded in a molecular cloud. But the dif-
fERENCE in absorption above and below the disk should be great.
Moreover, if the disk is really geometrically thin compared to the
size of the UC H ii region, we expect there to be a sharp dividing
line between the obscured side and the unobscured side, just as in
the Saturn’s rings analogy. Departing from the planet-ring anal-
ogy, we can also predict that in a disk—UC H ii region system, the
absorbing gas in the molecular disk would be well homogenized.
Such a disk would only form if the gas were rotationally sup-
ported. Thus, the rotation timescale would be much smaller than
the infall timescale, and any inhomogeneities entering the disk
would be quickly smoothed out by differential rotation. The pre-
dictions for a thin-thick molecular disk surrounding an UC H ii
region are a large difference in optical depths from one side to the
other, a sharp dividing line between the two sides, and struc-
turally smooth absorbing material.

G10.6 does not show evidence for a geometrically thin,
optically thick disk, and in fact it fits none of our three ob-
servational predictions for a thin-thick disk. First, Figure 2
shows that there is very high optical depth gas over most of the
face of the UC H ii region. While the southwestern edge has less
high optical depth gas than the rest, Figure 2 shows no direc-
tional preference at all for the apparent optical depth. The only
continuum emission without detectable absorption is the south-
ern spur (to which we return below). Second, there is clearly no
sharp dividing line, just a general trend of the higher optical
depth gas to be thinner. Third, the absorbing material is inhom-
geneous. At our full resolution, the optical depth varies greatly
on size scales (0.25) much smaller than the size of the UC H ii
region (1’’–2’) and larger than the synthesized beam (0.1’’).
The existence of the arcuate structures to the east has been inter-
preted as evidence that the surrounding molecular medium is
clumpy, and that the arcs are caused by ionizing photons leak-
ing out from the central UC H ii region (Sollins et al. 2005). The
existence of the arcuate structures to the east has been inter-
preted as evidence that the surrounding molecular medium is
clumpy, and that the arcs are caused by ionizing photons leak-
ing out from the central UC H ii region (Sollins et al. 2005). We
can confirm the clumpiness of the accretion flow with the op-
tical depth maps, which show variations in integrated optical
depth of as much as a factor of 8 in a projected distance of less
than 1000 AU. While not all of the variations need to be attrib-
uted to variations in column density, the other factors that con-
tribute to the optical depth, excitation temperature and ammonia
abundance, might not be expected to vary greatly in the molec-
ular gas. The gas distribution in G10.6 is not a geometrically
thin, optically thick accretion disk. Instead, the gas is in a flat-
tened, slowly rotating, molecular accretion flow.

Compared to the central mass, the mass of the accretion flow
is appreciable. Based on the hyperfine optical depth, and assum-
ing a temperature and ammonia abundance, we can calculate the
total molecular mass seen in absorption in the accretion flow.
Using 150 K for the excitation temperature of the gas (Sollins
et al. 2005), the peak column density of ammonia is greater than
1.2 × 10^{17} cm^{-2}. This a lower limit because there are points at
which the absorption in the satellite line saturates. Our integral
over the entire map therefore gives a lower limit. Assuming the
ammonia abundance is 10^{-7} relative to H_2 (van Dishoeck & Blake
1998), and adding a factor of 2 since we only detect the front half
of the accretion flow in absorption, the total molecular gas mass in
the molecular accretion flow is greater than 72 M_\odot. The as-
sumed abundance is the largest source of error here and could be
wrong by as much as an order of magnitude in either direction.
Using the radius of the UC H ii region to set the size scale, the
implied mass accretion rate is 0.02 M_\odot yr^{-1}. Sollins et al. (2005)
calculate that the central mass responsible for the inflow is roughly
150 M_\odot. It is entirely possible that the mass of the accretion flow
is comparable to the central stellar mass.

The total continuum flux is 2.44 Jy, so assuming constant
density, and electron temperature of 10,000 K and a physical
size of 8500 AU, the mass of the ionized gas is 0.22 M_\odot. Just by
looking at the continuum map it is clear that the density is not
uniform, and since we know there is ongoing accretion, the den-
sity profile should be proportional to r^{-3/2}. The mass, however,
depends strongly on the total size of the region in question. Thus,
the more spread out ionized gas will dominate the mass. For ex-
ample, even if we associate all the emission from the marginally
resolved peak of the continuum emission with a single density
enhancement, the most ionized gas mass we can possibly asso-
ciate with the peak is 0.0035 M_\odot. Keto (2003) pointed out that,
when estimating the Lyman continuum flux necessary to achieve
ionization balance, the density gradient can be very important.
This is because the recombination rate is proportional to density
squared. Because mass is proportional to density only to the first
power, the total mass is less sensitive to small high-density pock-
ets and will be dominated by the larger scale structures. Only for
a density profile steeper than r^{-2} will the mass be dominated by
smaller radii rather than larger radii.

4.2. Inclination of the “Disk”

Sollins et al. (2005) determined that the rotation axis of the
molecular accretion flow points northeast when projected into
the plane of the sky. Based on our data, the axis of rotation ap-
pears to be tipped away from the observer in the northeast. Even
though the molecular gas is not in a rotationally supported, geo-
metrically thin disk, the gas distribution is flattened, with denser
gas collected in the plane of the equator of the system. Since that
plane is tipped, we expect the densest gas to be preferentially in
the northeast. We have seen a hint of this already in Figure 6,
where the absorption from the main hyperfine component ex-
tends right down to the southwest edge of the continuum, while
the absorption from satellite component does not. To test for
this inclination quantitatively, we have analyzed the maps in Fig-
ure 2. For each of the four maps we have made 15 slices paral-
el to the axis of rotation, southwest-northeast. Then along each
slice we calculate a flux-weighted average position, i.e., the first
moment of the slice. In the continuum map, the average positions
follow the line closely and do not systematically deviate in one
direction or the other. By contrast, in the hyperfine optical depth
map, the average positions are all to the northeast, except at the
two points where the anomalous large line width clump has
dragged the average to the southwest. The highest density gas is,
on average, 0.08 northeast of the projected midplane of the continuum, and farther to the northeast if the large line width clump is excluded. Because the area over which the optical depth can be calculated is defined by the extent of the continuum emission, the mean positions cannot be wildly different. This emphasizes the significance of the offsets in position of the hyperfine optical depth from the continuum. These offsets are direct evidence that the “disk” is tilted, and the axis of rotation is inclined. Using the radius of the UC H II region, 1”, as a lower limit for the radius of the disk, a 0.08 offset is consistent with a tilt of the disk of 4°. Other direct evidence for this inclination has been found by E. Keto (2005, in preparation), who has detected redshifted H66α emission to the northeast of the UC H II region, within the notch in the continuum emission on that side. He has interpreted that gas as an outflow.

Another clue as to the inclination of the rotation axis is the strength of the absorption on the narrow spurs of continuum. On the northeast side of the continuum source there is the V-shaped notch mentioned above. Sollins et al. (2005) interpret this as a possible outflow cavity, and E. Keto (2005) has confirmed this. On the southwest side, E. Keto detects no corresponding blueshifted outflow, but the continuum does show a sharp-edged spur, reminiscent of the notch in the northeast. While the spurlike structures in the northeast show strong absorption in both apparent and hyperfine optical depth, the spur in the southwest shows only weak absorption in the apparent optical depth map, and no detectable hyperfine optical depth. This is further evidence that the high-density gas in front of the continuum source is in the northeast because of a flattened density profile and the rotation axis being tipped away from the observer in the northeast. However, we should note a possible alternate explanation. We cannot rule out the possibility that the southern spur is the limb-brightened edge of a photoionized molecular clump, just like the arcs to the east. In that case, the clump might be closer along the line of sight, not physically associated with the main UC H II region, and therefore not obscured by the densest molecular gas.

4.3. A New Phase of Massive Star Formation

The data on G10.6 are unique in the study of accretion onto massive stars because of their spatial resolution, and because the interpretation is not model dependent. Disklike structures have been detected around a number of very early B-type stars. Chini et al. (2004) detected a 10,000 AU, morphologically disklike structure at 550 AU resolution. Kinematic observations at 13,000 AU resolution show that the disk is rotating on that larger size scale. In IRAS 20126+4104, IRAS 18089–1732, and AFGL 5142, flattening and rotation in dense molecular gas has been detected at roughly 5000 AU resolution. In all three of those cases the sources have infrared luminosities corresponding to early B stars (Zhang et al. 1998, 2002; Beuther et al. 2004). In G192.16–3.82, Shepherd & Kurtz (1999) find a velocity pattern consistent with rotation in water maser spots at a 1000 AU spatial scale, also around an early B star. In all these cases, molecular gas is found to be in rotation, in some cases apparently Keplerian rotation, around early B-type or even late O-type stars. All are consistent with the existence of rotating, molecular accretion disks that, in many respects, are larger versions of the disks observed around low-mass protostars. In contrast to previous work, in G10.6 we have 500 AU physical resolution in the thermally emitting molecular gas. The spatial resolution is enough to completely resolve the motions involved. The kinematics and optical depths are fairly unambiguous. The densest gas is flattened, and the velocities clearly show infall and slow rotation.

G10.6 itself contrasts with objects from previous massive star disk studies in that it cannot be interpreted as a scaled-up version of low-mass star formation. All the cases cited above (IRAS 20126, IRAS 18089, G192.16, M17, and AFGL 5142) are consistent with the central object being a single stellar system of up to 20 $M_\odot$. In most of these objects the existence of a bipolar outflow indicates ongoing accretion. The analogy to the formation mechanisms of low-mass stars is fairly straightforward, scaled up in size and mass, although a key difference is ratio of disk mass to stellar mass, small for low-mass stars, but apparently large for high-mass stars. In G10.6, the central source is at least 150 $M_\odot$, close to 10⁶ $L_\odot$, and is almost certainly not a single star or binary. At the edge of the UC H II region, at a radius of 5000 AU, the molecular gas is clearly moving inward, and Keto (2002a) detects inward motions in the ionized gas down to radii of less than 1000 AU. While we cannot say how or if the inward-moving gas actually accretes onto one or more of the central stars, we can say with great certainty that inward motion continues in the molecular gas from the 0.5 pc scale (Ho & Haschick 1986; Keto et al. 1988) down to thousands of AU. This is a single continuous accretion flow traceable over 2 orders of magnitude in size, toward a group of young massive stars. This suggests a completely different phase or mode of star formation than that seen in low-mass stars, or in the preceding examples of individual massive young stars.

5. SUMMARY

We have used the strong 23 GHz radio continuum emission from the UC H II region G10.6–0.4 to serve as a backlight for examining the foreground molecular material seen in absorption. Using the VLA, we have achieved very high angular (0.08”) and spatial (500 AU) resolution. In the past, such resolutions have not been possible for studying the circumstellar environment of massive young stars. Making use of the hyperfine structure of the NH$_3$ (3, 3) inversion line, we are sensitive to optical depths of up to 80. This allowed us to investigate the structure of the densest circumstellar material. We find that in the densest material, the structure is flattened, with an aspect ratio of 5. The structure is displaced with respect to the mean continuum emission, consistent with a tilt of the disk along the line of sight at 4°, away from the observer in the northeast. The flattened structure has a mass of 72 $M_\odot$, much larger than the ionized gas in the H II region of 0.2 $M_\odot$. The velocity pattern within the circumstellar material, as well as its clumpiness, suggest a dynamically collapsing structure that is not centrifugally supported. The implied infall rate is very high, on the order of 0.02 $M_\odot$ yr$^{-1}$. The kinematics of the circumstellar material, which agree with the kinematics of the ionized gas within the H II region, suggest that this infalling material continues across the ionization front. Because we do not know how much mass is actually being accreted by the stars, or how much mass is leaving the system in the outflow, it is impossible to know for sure whether G10.6 is in quasi-static equilibrium, or if it is evolving dynamically. However, the very high mass and luminosity involved mean that this is a different type of object than the individual high-mass protostars that have been investigated in the past.

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