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THE BROAD-LINE REGION AT THE CENTER OF THE GALAXY

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ABSTRACT

The high-velocity wings of the Brα (4.05 μm) line at the Galactic center have been mapped with a 2".5 beam and at a velocity resolution of 400 km s^{-1}. The broad-line region is spatially resolved, with a characteristic linear dimension of ~3" (FWHM). The peak intensity of the high-velocity line emission is coincident with the position of the source IRS 16 Center, and its intensity distribution about that object is approximately symmetric. The observed motions appear to be neither rotational nor due to well-collimated jets. In addition, the spatial extent of the broad-line emission implies that they are not infall onto or outflow from the immediate vicinity of a compact object. We suggest that the broad-line emission either is from more than one compact wind source or is the result of an interaction between an ultrahigh velocity wind (which is undetected at present) and slower moving ionized gas in the "bar" whose trajectory brings it close to the wind source. The source of the unseen wind could be Sgr A*, IRS 16C, or any of the other components of IRS 16.

Subject headings: galaxies: internal motions — galaxies: nuclei — galaxies: The Galaxy — infrared: spectra — line profiles

I. INTRODUCTION

Understanding the dynamics of the ionized gas at the center of the Galaxy is an important step toward determining the nature of the objects which dominate the energetics there. In recent years improvements in the techniques of small beam mapping and spectroscopy have led to a greatly increased understanding of the ionized gas motions in the Galactic center, especially those which exist on a 1 pc scale and larger (e.g., Lo and Claussen 1983; Serabyn and Lacy 1985). Despite these improvements, highly divergent suggestions for the nature of the active and ionizing source (or sources) within the central 0.1–0.2 pc must still be considered seriously (e.g., Brown 1982; Lacy, Townes, and Hollenbach 1982; Lebofsky, Rieke, and Tokunaga 1982; Lo and Claussen 1983; Gatley *et al.* 1984; Ozernoy 1984*a*, *b*; Crawford *et al.* 1985; Allen and Sanders 1986). Thus further and more discriminatory observations are required. In particular, these observations must include additional measurements of that component of the ionized gas which is in closest proximity to the active source(s), which are thought to reside within or close to IRS 16, the central infrared object in the Galaxy.

Hall, Kleinmann, and Scoville (1982) discovered that the 2.06 μm helium line at the position of IRS 16 is unusually broad. Geballe *et al.* (1984; hereafter Paper I) confirmed this and found from their observations of the 4.05 μm Brα line that the same broad (FWZI ≈ 1400 km s^{-1}) emission is present in hydrogen recombination lines, that the high-velocity gas is localized near IRS 16, and that the helium abundance in this gas is not highly unusual. These discoveries made clear the uniqueness of the IRS 16 region and pointed out new observational means to study it. However, the region of interest is only a few arc seconds across, and until now the dimensions of the broad-line region were not accurately known, nor was its position accurately defined with respect to IRS 16, which is now known to consist of several compact objects (Storey and Allen 1983; Henry, Depoy, and Becklin 1984; Allen and Sanders 1986; Forrest, Pipher, and Stein 1986), or with respect to Sgr A*, the nonthermal radio source in the nucleus (Balick and Brown 1974). Additional measurements of the Brα line at higher spectral and spatial resolution are necessary, in order to characterize more accurately the broad-line profile, to determine its spatial extent, and possibly to associate the broad-line emission with individual objects in the IRS 16/Sgr A* complex. Herein we report measurements which represent a step toward these goals.

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II. OBSERVATIONS

All of the observations were made at the United Kingdom Infrared Telescope (UKIRT) during 1985 June 16–19, using the facility seven-channel, liquid and solid nitrogen-cooled grating spectrometer (Wade 1983). The measurements utilized a 2".5 diameter aperture and a grating which provided a velocity resolution of 400 km s^{-1}. These compare with the 4".2 beam and 550 km s^{-1} resolution of the spectra in Paper I. Standard chopping and nodding practices were employed, using east-west beam separations of ~60". In order to flux calibrate the Galactic center data, spectra were also obtained of BS 7063 (G5 II), which has a negligibly weak Brα absorption line. Line fluxes, as given in Figure 1, are thought to be accurate to ±20%. Wavelength calibrations were achieved by observing Brα in the planetary nebulae NGC 6572 and BD +30°3639.

Spectra near IRS 16 were obtained at 34 positions on a 1".5 grid. The (0, 0) position of the grid was measured to be 1".8 east and 6".6 south of IRS 7. The accuracy in positioning the telescope on this grid was at least 0".3 at each position. The seeing was better than 1", and sky conditions were photometric. The spectra were obtained over a velocity range of ~3000 km s^{-1}, sampled every 92 km s^{-1} over the central 1800 km s^{-1}. The integration time for most of the grid was 8 minutes per position. In addition to the grid measurements, spectra of Brα and Brγ in a 4".5 beam were obtained at the map origin.

GALACTIC CENTER H I 5 - 4 (2.5")

DEC OFFSET (arcsec) \ RA OFFSET (arcsec)	+3.0	+1.5	0.0	-1.5	-3.0	-4.5	-6.0	-7.5
+3.0	29. 2.6 30 <200	17. 2.0 0 <200	10. 1.2 -50 <200	11. 1.0 -10 300	19. 0.8 -30 30			
+1.5	56. 3.8 10 ≤200	24. 3.3 -20 ≤200	17. 2.4 -20 250	13. 1.6 -30 400	16. 3.8 10 ≤200	16. 1.7 -80 250		
0.0	22. 3.8 -30 <200	21. 4.0 -30 <200	23. 4.0 -120 250	21. 3.6 -130 350	29. 3.9 -100 350	31. 3.8 -120 350	24. 3.1 -90 ≤200	11. 2.3 -100 ≤200
-1.5	6. 1.8 30 250	19. 3.8 -40 <200	21. 4.8 -110 <200	19. 4.9 -150 300	20. 3.9 -140 450	38. 4.9 -180 500	23. 3.3 -150 450	
-3.0	8. 2.1 100 300	11. 3.0 90 400	11. 4.1 -60 <200	11. 3.5 -14 400	17. 4.2 -210 400	32. 5.0 -260 400		
-4.5			8. 3.4 -60 250					
-6.0			4. 3.8 -30 ≤200					

F_c (10^{-18} W/cm^2 μm)
F_{line} (10^{-19} W/cm^2)
v_{peak} (km/s)
FWHM (km/s)

FIG. 1.—Observed parameters of the 2″.5 beam Brα spectra near IRS 16. The (0, 0) position corresponds to R.A. = $17^h42^m29^s.48$, decl. = −28°59′19″.5 (1950). Velocities are given with respect to LSR; uncertainties are typically 50 km s^{-1} for a line of strength 2×10^{-19} W cm^{-2}. The FWHMs are deconvolved, assuming a Gaussian intrinsic shape of the line core.

III. RESULTS

a) Line Profiles

i) Raw Spectra

The basic parameters describing the 34 Brα line profiles measured with the 2″.5 beam are listed in Figure 1. Figure 2 contains two rows of actual spectra, corresponding to cuts in right ascension through the Galactic nucleus at declinations of −28°59′18″.0 and 19″.5 (1950). In these one can see (especially in the red wing) that the intensity at the highest velocities reaches a maximum at the approximate right ascension of IRS 16 ($17^h42^m29^s.45$, 1950). The broadest lines, as measured by the extent of the red wing, also occur near the right ascension of IRS 16 in this figure. The high-velocity wings were also present in the 4″.5 beam spectra of Brα and Brγ at IRS 16 (detected for the first time in the latter).

The central velocity of the narrow component shifts by ~100 km s^{-1} across the spectra in Figure 2, in a manner generally consistent with Galactic rotation and with previous observations (Lacy *et al.* 1980; Geballe *et al.* 1982). At intermediate velocities there are some interesting changes in the profiles over small angular distances; e.g., in the spectra at −28°59′18″ note the rapid shift from a strong redshifted shoulder at $29^s.48$ to a blue shoulder at $29^s.36$.

The rather low intensity levels of the high-velocity wings in the Brα spectra make difficult a visual comparison of their intensities in individual grid spectra. In order to view at higher signal-to-noise ratio the intensity and velocity distribution of the high-velocity gas near IRS 16, we have summed 2″.5 beam spectra along the Galactic plane on either side of IRS 16 Center (hereafter IRS 16C) and above and below the plane adjacent to that source. These composite spectra, each consisting of four individual spectra and corresponding to mean distances of ~2″ from IRS 16C, are presented in Figure 3. In this figure it is apparent that the intensities of the wings are approximately the same at equal distances from IRS 16C and that there is no evidence for different distributions of high-velocity red and blue line emission; i.e., no evidence for rotation or bipolarity. In particular, note that the strengths of the well-resolved red wings in Figure 4 do not scale with the strengths of the line peaks.

ii) Convolutions

Although both redshifted and blueshifted high-velocity wings are detected in these spectra, quantitative analysis of the blueshifted wing proved difficult for three reasons. First, the narrow-line component near IRS 16 is shifted to the blue with respect to the center of the broad-line component, so that less of the blue wing than the red wing is free of blending. Second, a singlet plus triplet line blend of He I 5*g*–4*f*, which contains half of the total intensity of He I 5–4, is situated 240 km s^{-1} to the blue of H I Brα; because of uncertainties in the abundance ratio [He]/[H] and in the ionization state of the gas, the contribution of this helium line to the profile is uncertain. Third,

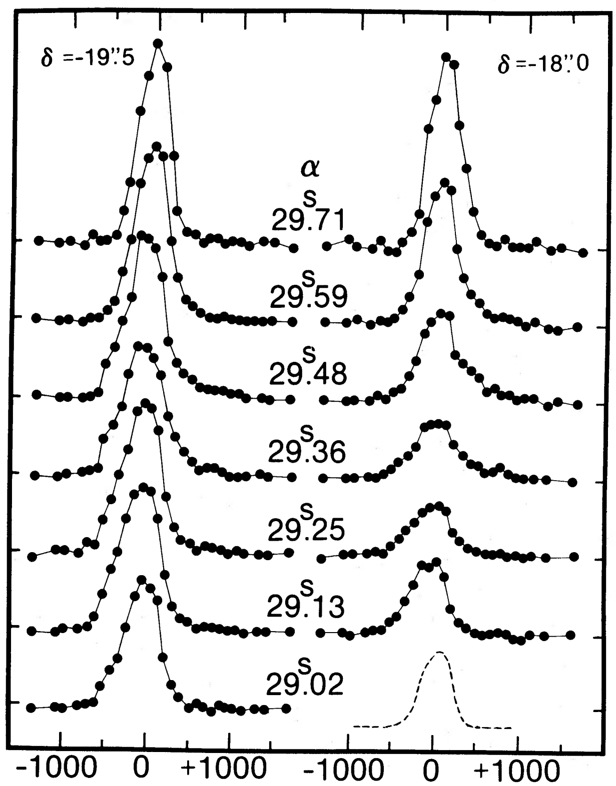

FIG. 2.—Two rows of Brα spectra in right ascension, obtained in a 2″.5 aperture and at declinations which pass through IRS 16. Error bars are comparable to the size of a data point. The instrumental profile is shown at bottom right.

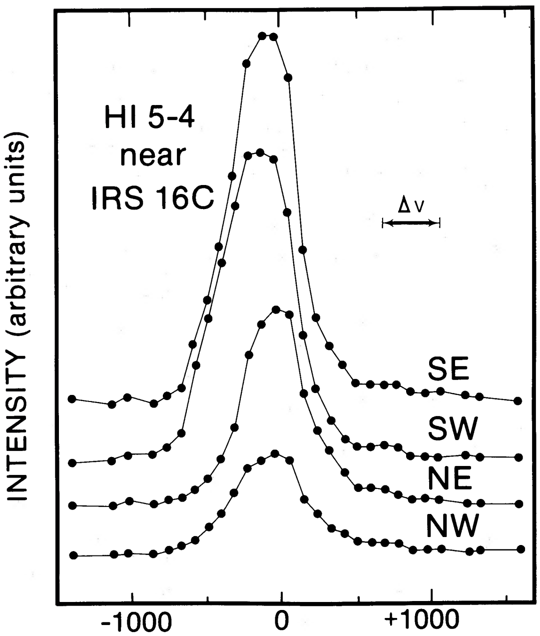

FIG. 3.—Composite Brα spectra roughly 2″ distant from IRS 16C, approximately along and perpendicular to the Galactic plane. Each is the sum of four individual 2″.5 beam Brα spectra listed in Fig. 1.

during these observations the instrumental profile was asymmetric, having a steeper slope to the red of the line peak than to the blue (see the instrumental profile in Fig. 3); the effect of this is that the central narrow component of the line blends smoothly into the blue wing, making it difficult to estimate the strength of that wing. Consequently, in the following sections we concern ourselves largely with the reshifted high-velocity wing.

The intrinsic strength and extent of the wings may be estimated by attempting to match the observed spectrum with trial line profiles convolved with the instrumental profile. We have taken as the instrumental profile the observed spectra of the Brα line in the planetary nebula NGC 6572. Representative examples of convolutions are shown in Figure 4. It is clear that for the spectra near IRS 16, a Gaussian trial function alone leads to an unsatisfactory fit to the wings of the observed line, but that a combination of a narrow (FWHM $\approx$ 250 km s^{-1}) Gaussian and a broad and flat component provides a fit which is nearly identical, within the noise, to the observed spectrum. Figure 4 also demonstrates that the strength of the red wing observed at velocities higher than $\sim$600 km s^{-1} is a fairly accurate indicator of the strength of the broad-line component, a result that we use below. Finally, we note that in the best-fitting trial functions the line emission extends somewhat farther to positive than to negative velocities. For example, in Figure 4*b* the extrema are -600 and $+800$ km s^{-1}. Because of the uncertainty in the proper fit to the line profile at high negative velocities (discussed above), we are not completely convinced of this difference in positive and negative extrema. Lower resolution observations both prior and subsequent to these (Paper I; Geballe 1987), when the instrumental profile was symmetric, show a pedestal which is roughly as extensive and strong to the blue of 0 km s^{-1} (LSR) as it is to the red. Further observations, at higher spectral resolution than those of the present experiment, are necessary to clarify the profile of the high-velocity component.

b) Intensity Distributions

A map of the intensity of the high-velocity redshifted gas is shown in Figure 5. It was derived from the 2″.5 beam spectra (including those in Fig. 3) by integrating the observed line intensity over the velocity interval $600 < V < 1000$ km s^{-1}. The positions of the infrared, near-infrared, and radio sources in this region are superposed on the map. The coordinates were obtained from Forrest, Pipher, and Stein (1986), who have simultaneously measured all infrared positions relative to IRS 7, an achievement which is critical for the present study. The map clearly demonstrates that the high-velocity redshifted gas peaks at IRS 16, with the peak closest to IRS 16C. In particular, the high-velocity gas is not peaked or centered at Sgr A*. The highest contours on the map neatly enclose the IRS 16 complex and are elongated approximately along the Galactic plane (note, however, that the two highest contours are based on data from very few pixels and thus their precise shapes are rather uncertain). The lower two contours appear slightly elongated perpendicular to the plane. A fundamental result of these measurements is that the brightest region of broad-line emission extends over a few arcseconds. The region is partially resolved in both spatial dimensions. The characteristic observed FWHM of the region is $\sim$4″. Allowing for the 2″.5 aperture, the actual FWHM is $\sim$3″.

The total observed flux in the red wing of the Brα line, integrated over the entire map (including a correction for beam overlap), is 4.5×10^{-20} W cm^{-2}. The flux in the 2″.5 beam at each of the two brightest positions (R.A. = 29ˢ.48, decl. = −18″.0 and −19″.5) is 1.3×10^{-20} W cm^{-2}. The total flux in the broad-line component, assuming a flat velocity profile for it and that the unclosed contours off the map do not contain significant additional flux, is $\sim 2.5 \times 10^{-19}$ W cm^{-2}. Assuming 1.2 mag of extinction at 4.05 μm (Wade *et al.* 1987) and a distance of 8.5 kpc to the Galactic center (Knapp 1983), the luminosity of the broad Brα line emission is $\sim 20\ L_{\odot}$. The corresponding flux of ionizing radiation is but a very small fraction of that emitted in the Galactic center (see Paper I for a discussion of this point).

The spatial distribution of the total Brα line intensity in the central few arc seconds of the Galaxy is shown in Figure 6. This map is also derived from the 2″.5 measurements and should be compared with the map of the red wing of the line (Fig. 5). The brightest emission from Brα in the mapped region lies to the south and southwest of the IRS 16 complex, near IRS 21 and IRS 2/13. The IRS 16 complex, where the broad lines are found, lies on a north-south gradient of Brα emission. Thus the maps of high velocity and total integrated Brα emission bear little resemblance to one another. The total intensity map (Fig. 6) closely resembles maps of the thermal infrared continuum in this region (e.g., in Becklin *et al.* 1978 and Gezari *et al.* 1985). In some respects the Brα total intensity map (Fig. 6) is similar to the Brα map of Storey and Allen (1983), which was made using a similar angular resolution. The major differences are: (1) we observe no enhancement of total line intensity at IRS 16NE, whereas they found a rather prominent peak there, and (2) we clearly detect line emission at IRS 16C (both at high and at low velocities), whereas they detected no ionized gas there. We have no explanation for the discrepancies, but note that the present line measurements were obtained using a stronger H I line, at considerably higher spectral resolution and simultaneously with the adjacent continuum so that accurate removal of the continuum posed no serious problem. We note, however, that a recent 1″ resolution Brα map made by

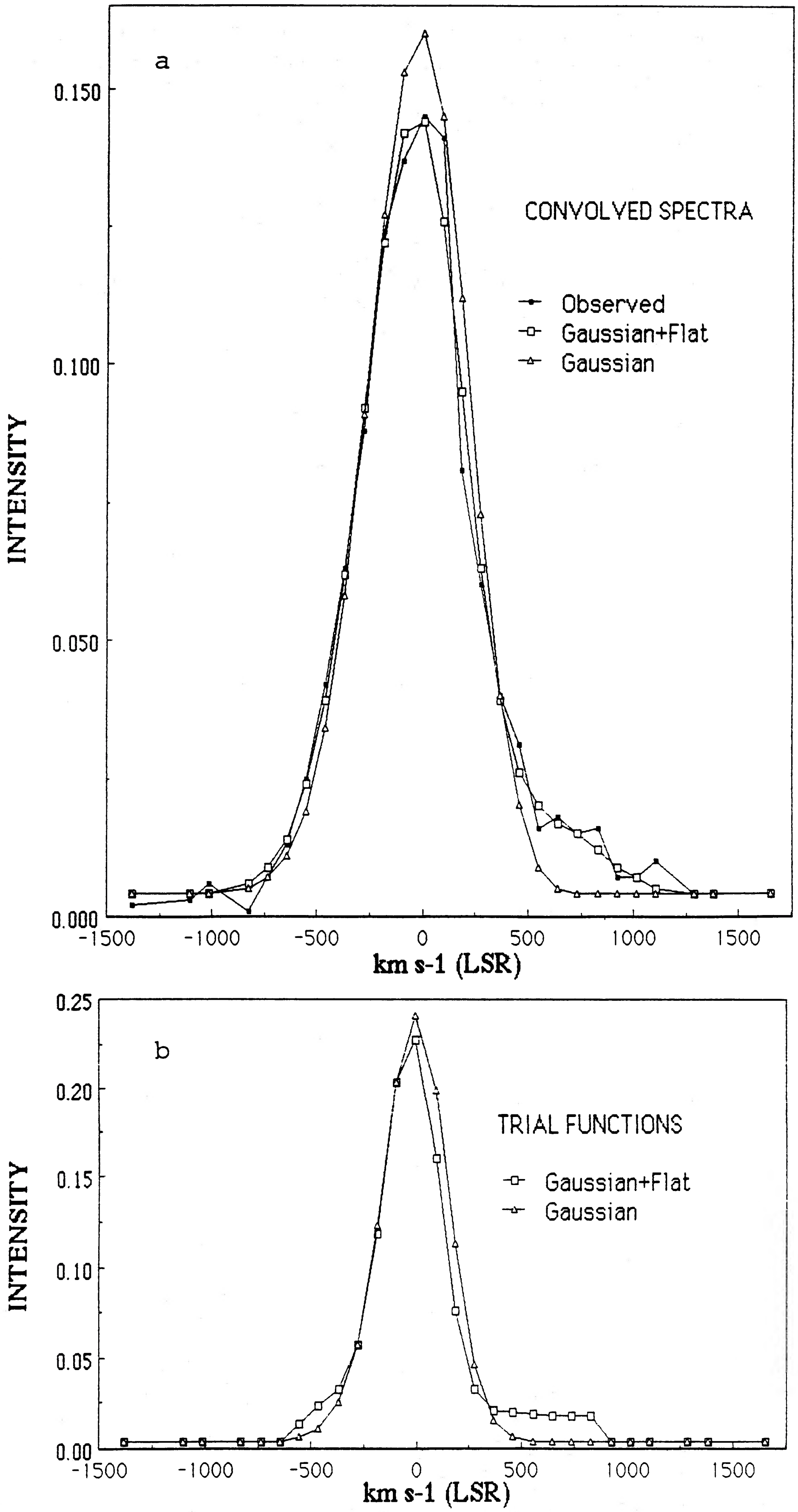

FIG. 4.—(*a*) Convolutions of two trial functions with the instrumental profile; the observed composite Brα spectrum 2″ NW of IRS 16 is also shown. (*b*) The trial functions.

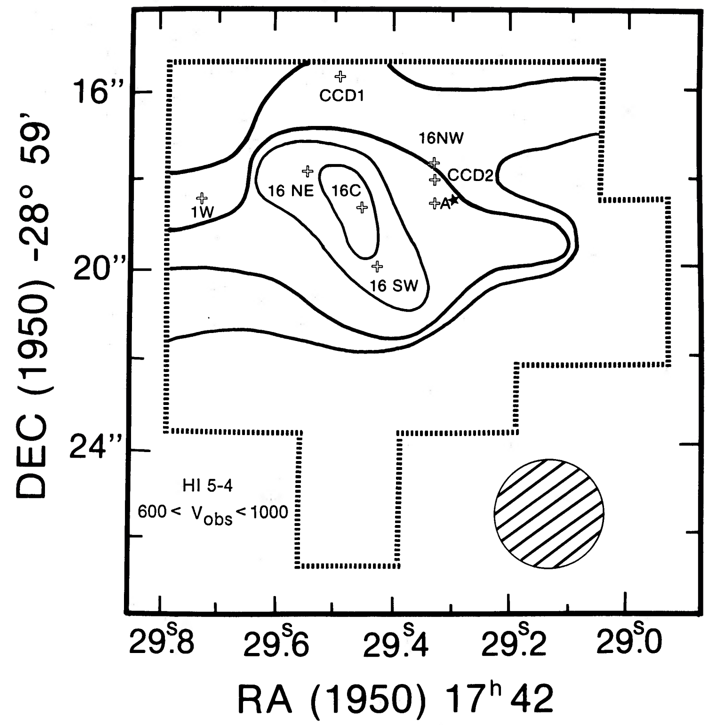

FIG. 5.—Map of the redshifted high-velocity Brα line intensity in the Galactic center, made with a 2".5 beam. The outermost contour ($\sim 1.5\ \sigma$) and the spacing between contours are both 3.1×10^{-21} W cm^{-2} in the aperture. The outlined area is the region mapped. Locations of various Galactic center sources are indicated.

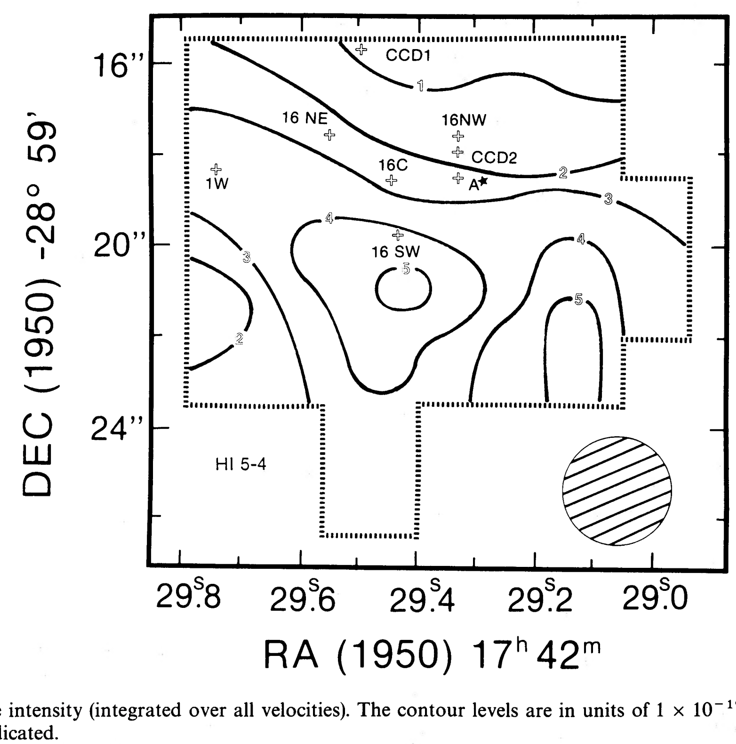

FIG. 6.—Map of the total Brα line intensity (integrated over all velocities). The contour levels are in units of 1×10^{-19} W cm^{-2} in a 2".5 beam. Locations of various Galactic center sources are indicated.

Forrest *et al.* (1987), using a CVF with $\lambda/\Delta\lambda \approx 75$, indicates that much of the Brα line emission from the IRS 16 region is localized in compact regions, one of which is coincident with IRS 16NE. Their lowest contour corresponds to a surface brightness approximately 4 times greater than that of the broad-line component as observed by us. One way that their map and ours can be consistent is if all of the high-velocity line emission seen by us is concentrated in these knots, which then must contain little low-velocity gas. Alternatively, if the high-velocity gas is diffuse, then the Forrest *et al.* knots contain predominantly low-velocity gas.

IV. DISCUSSION

The most significant results of this research are: (1) the improved spatial registration of the broad-line emission with respect to the IRS 16 complex. (2) the determination that the broad-line region is spatially extended, and (3) the lack of bipolarity in the velocity field of the broad-line region. In particular the latter two results greatly constrain the possible interpretations of the broad-line region. The implications of all of these results are discussed below.

a) Location and Velocity Distribution of the Broad-Line Region

The distribution of the high-velocity ionized gas, as revealed in the Brα map of Figure 5, shows that most of that gas is located within the IRS 16/Sgr A* complex. The peak of the broad-line emission is most closely associated with the infrared object, IRS 16C. The map appears to exclude a direct physical association of the bulk of the emission with most of the nearby sources (IRS 16NW, IRS 1W, CCD1, CCD2, and Sgr A*). However, the elongation of the brighter contours of the map in the NE–SW direction suggests that there may also be a physical correspondence with IRS 16NE and SW. Henry, DePoy, and Becklin (1984) found that all of the IRS 16 sources have 1–2 μm energy distributions similar to those of early-type stars and infer a luminosity of $\sim 1 \times 10^7\ L_\odot$ for IRS 16C (assuming its 1–2 μm radiation is thermal and that $A_v = 34$ mag). The luminosities of IRS 16NE and SW were not estimated by Henry, DePoy, and Becklin, but would be similar under similar assumptions. These and other less direct arguments indicate that the IRS 16 complex may account for the majority of the luminosity and ionizing radiation in the Galactic center. Thus, it is not surprising that the broad-line region may be associated with extraordinary activity of one or more of the sources in this complex.

The observed Brα velocity profiles and their spatial distribution lead to more stringent requirements on the allowed motions of the high-velocity gas than were previously known. Because the red and blue wings have similar distributions on all sides of IRS 16C, both pure rotation and well-collimated jets can be excluded, unless they occur largely in the plane of the sky and involve substantially higher velocities than have been observed to date. Small-scale turbulent motions have already been ruled out by the presence of high-velocity He I 2.06 μm line emission (Paper I). Therefore, only roughly spherically symmetric radial motions, poorly collimated jets, or sheetlike motions are left as possible explanations.

Recently, two interpretations of the high-velocity gas motions have been proposed. Serabyn and Lacy (1985) obtained spectra of the lower velocity ionized gas at distances of $\sim$0.1–1.5 pc from IRS 16/Sgr A*, which they interpret as material in orbit about and falling toward a massive object at or very near the position of IRS 16. They and Crawford *et al.* (1985) suggest that the high-velocity gas observed in the Brackett and helium lines may be bound to such an object. Note that for the case of gravitational infall (or rotation) the mass within 0.06 pc (1''.5) of IRS 16C, estimated by applying the virial theorem to the present data, is $\sim 3 \times 10^6\ M_\odot$, a value which is similar to that in the model of Serabyn and Lacy. On the other hand, we and others have previously suggested that, in view of the relative lack of gas in the central 1–2 pc and the existence of shocked molecular hydrogen at the edges of this cavity, a natural way to account for the high-velocity line emission at IRS 16 is by a wind (Gatley *et al.* 1984; Paper I). In this case, the mass within IRS 16 is indeterminate, because velocities in a wind are not normally an accurate indicator of the mass of its source.

b) Implications of the Observed Spatial Extent of the Broad-Line Region

i) *The High-Velocity Motions as a Primary Mass Flow*

We initially attempt to understand the broad-line region under the hypothesis that the observed spatially extended high-velocity emission is a single mass-loss or infall phenomenon occurring within IRS 16. Previously because of the unknown angular extent of the high-velocity wings, the estimate of the mass-loss rate under the above hypothesis had an uncertainty of 2–3 orders of magnitude (Paper I). The present data allow the mass-loss rate to be constrained to a considerably higher degree and also imply a large inner surface from which the mass loss is occurring or onto which the infall is depositing material.

We consider the case of a constant velocity and constant temperature ionized flow (for which $n_e \approx r^{-2}$) originating at a distance R_s from a central object, in which case half of the recombination line emission occurs within a distance R_s of that inner surface (see Wynn-Williams 1984). From Figure 4, R_s is $\sim$0''.75, or 0.03 pc and, thus, in this simplest of models, *the observed high-velocity ionized gas is quite remote from its source.* Using the above value of R_s and the estimated broad-line flux the electron density at the inner surface is $n_e \approx 2 \times 10^4$ cm^{-3}. The mass-loss (or infall) rate from this surface is $\sim 4 \times 10^{-3}$ $M_\odot$ yr^{-1} for an outflow velocity of 700 km s^{-1}. These values imply that if, for example, the high-velocity gas is an outflow from IRS 16C, that outflow bears no resemblance to those observed in the vicinities of massive young stellar objects; in those objects the H I line-emission region is unresolved and electron densities are much higher (see, e.g., Simon *et al.* 1983; Persson *et al.* 1984).

Stated differently, the weakness of the high-velocity line emission at IRS 16 together with its large spatial extent do not permit an interpretation of the line emission as originating in a constant velocity outflow from a single region of stellar, superstellar, circumstellar, or black hole accretion disklike dimensions. Similarly, infall of the line-emitting gas toward such a pointlike object is not allowed. Because of the $n_e{}^2$ dependence of the Brα emission, even if the restriction of constant velocity is relaxed considerably, a radial outflow from or infall toward a single pointlike source will produce a more pointlike broad-line emission region than we have observed. One should also consider if variation of temperature in a radial flow might prevent recombination line emission from appearing pointlike. Temperatures close to the source of such a flow might be typical of a corona, suppressing Brα line emission there.

However, it appears unlikely that high gas temperatures would persist beyond several radii of the start of the flow and overcome the n_e^2 dependence of the line emission out to distances of $\sim$0.03 pc.

If two or more outflows (or infalls) are occurring simultaneously within IRS 16, the observed extent of the broad-line region could be understood in terms of pointlike sources, which are not spatially resolved in the present experiment. In this case the mass-loss rate from each source could be considerably lower. However, it would seem unlikely that two or more objects in the Galactic center are engaged simultaneously in this kind of activity. It is also questionable whether the more extended, lower level, high-velocity line emission in Figure 5 can be understood on the basis of pointlike sources. Similarly, the possibility that the high-velocity line emission is due to a number of discrete flows through the central one-tenth parsec seems unlikely, because of the similarity of line profiles at different positions near IRS 16. However, Brα velocity-resolved spectroscopy at considerably higher spatial resolution is required to better test the multiple source and multiple flow hypotheses.

ii) *The Broad-Line Region as a Secondary Mass Flow*

From the above discussion, it appears that if only a single source is involved then the observed high-velocity ionized gas is remote from that object which is the ultimate cause of its motion. If so, then any successful explanation of the broad-line region must include a means of producing the extended emission without an observed pointlike concentration of line-emitting ionized gas. Thus, in any such model the presently observed broad lines are a secondary effect of an active source in the Galactic center.

One possible set of models involves a means of transporting ambient gaseous material to within a distance of $\sim$0.03 pc from this object (e.g., IRS 16C) and some mechanism, presumably not yet directly observed, which interacts with this material, causing the observed high-velocity flow. At a distance of 0.03 pc, radiation pressure would be capable only of accelerating ionized gas to 1% of the observed velocity, even if the luminosity of IRS 16C is that of the entire Galactic center (3×10^7 $L_\odot$) and if gravity is neglected. Thus another mechanism for momentum transfer must be sought. We suggest that an ultrahigh velocity mass-loss wind could be the transfer agent. The postulated wind must carry off momentum at the same rate as does the observed wind but must have escaped detection. In view of the difficulty of detecting the emission at 700 km s^{-1}, the present nondetection of a higher velocity wind is not a serious observational constraint. Clearly, if such a wind had a velocity even 5 times higher than the observed gas, it would not have been detected in the present experiment or by any previous observation.

In this picture ionized gas in Sgr A which approaches the wind source would be deflected from the source. The type of interaction would depend on the densities of the wind and the ambient gas at their interface. If the ambient gas has roughly the same density as the wind, as seems likely, much of the observed high-velocity line emission would occur in an interaction zone where the ultrahigh velocity wind is shocked and strongly decelerated. Equating ram pressures in the case of a 3000 km s^{-1} wind, a mass-loss rate of 4×10^{-3} $M_\odot$ yr^{-1}, and approaching ambient gas of density 3×10^4 cm^{-3} and velocity 100 km s^{-1} results in an interaction zone with a characteristic dimension of a few arc seconds, consistent with the observed size of the broad-line region. Morris and Yusef-Zadeh (1987) have proposed that a small hole in the radio emission close to IRS 16/Sgr A* is a cavity swept out by an energetic wind, a scenario similar to the one proposed here.

The above model, possibly to its detriment, postulates the existence of a highly unusual phenomenon, an ultrahigh velocity wind. The model does not account in a natural way for the spatial coincidence of the broad-line region and the bright compact infrared sources within IRS 16, unless these sources are related to the generation of the high-velocity wind or to the zone of interaction. However, in terms of the morphology and dynamics of the central few parsecs of the Galaxy the model appears to have several attractive aspects. Indeed, it fits well with current suggestions that the bulk of the ionized gas in Sgr A exists in streams passing near to, and possibly falling into, the Galactic central few tenths of a parsec (Lo and Claussen 1983; van Gorkom, Schwartz, and Bregman 1985; Serabyn and Lacy 1985). Because it requires only proximity of the wind source to a plentiful supply of gas, the model naturally accounts for the "peculiar" location of IRS 16 on the edge of the ionized gas "bar." A gradient in the density of the bar could account for the difference in the red and blue velocity extrema of the Brα line, which we may have observed. The interaction of the wind and the bar material might also account for the high electron temperature which is found in the central several arc seconds by the radio recombination line observations of Brown and Liszt (1984) and by van Gorkom, Schwarz, and Bregman.

Although IRS 16C could well be the source of the proposed wind, the wind source is not constrained to be coincident with the peak of the broad-line emission, unless the low-velocity ionized gas with which it interacts is distributed uniformly about the source. This is definitely not the situation at IRS 16 (see Fig. 6). Therefore, other objects, most notably Sgr A*, are plausible candidates for the wind source. We emphasize that the proximity of such unusual phenomena as the broad-line region and Sgr A*, together with their location on the same edge of the ionized gas bar, is circumstantial evidence that the two phenomena are related. Indeed, without such an association the role played by Sgr A* in the activity of the Galactic center is unclear, and possibly superfluous. It may be significant that in the most recent 1″ resolution Brα image of Forrest *et al* (1987) Sgr A* appears to be situated in a cavity in the ionized gas, as would be expected in this model.

In summary, we propose that the observed broad-line region may mark the zone of interaction of a fast wind from one of the compact objects (possibly Sgr A*) within the IRS 16 complex with ionized gas whose trajectory brings it within $\sim$0.03 pc of the wind source. The interaction results in the observed ejection of gas from the IRS 16/Sgr A* complex at $\sim$700 km s^{-1} and at rate of $\sim 4 \times 10^{-3}$ $M_\odot$ yr^{-1}.

V. CONCLUSION

The broad-line region of ionized gas at the Galactic center has a characteristic radius of about 0.06 pc and is centered at IRS 16C, not at Sgr A*. The high-velocity (700 km s^{-1}) gas motions are not dominated by a rotational component and are not narrow jets. The large size of the broad-line region implies that the motion of the gas is not outflow directly from or infall directly onto a single compact object. Instead the broad-line emission may delineate ionized gas flows, possibly originating from several compact objects, or the interaction of ionized gas passing through the Galactic center with an as yet undetected ultrahigh velocity wind emitted by Sgr A* or one of the compact objects in the IRS 16 complex.

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REFERENCES

Allen, D. A., and Sanders, R. H. 1986, *Nature*, **319**, 191.
Balick, B., and Brown, R. L. 1974, *Ap. J.*, **194**, 265.
Becklin, E. E., Matthews, K., Neugebauer, G., and Willner, S. P. 1978, *Ap. J.*, **219**, 121.
Brown, R. L. 1982, *Ap. J.*, **262**, 110.
Brown, R. L., and Liszt, H. S. 1984, *Ann. Rev. Astr. Ap.*, **22**, 223.
Crawford, M. K., Genzel, R., Harris, A. I., Jaffe, D. T., Lacy, J. H., Lugten, J. B., Serabyn, E., and Townes, C. H. 1985, *Nature*, **315**, 467.
Forrest, W. J., Pipher, J. L., and Stein, W. A. 1986, *Ap. J. (Letters)*, **301**, L49.
Forrest, W. J., Shure, M. A., Pipher, J. L., and Woodward, C. E. 1987, in *The Galactic Center*, (*AIP Conf. Proc.*, **155**), ed. D. A. Backer (New York: AIP), p. 153.
Gatley, I., Jones, T. J., Hyland, A. R., Beattie, D. H., and Lee, T. J. 1984, *M.N.R.A.S.*, **210**, 565.
Geballe, T. R. 1987, in *The Galactic Center*, (*AIP Conf. Proc.*, **155**), ed. D. A. Backer (New York: AIP), p. 139.
Geballe, T. R., Krisciunas, K., Lee, T. J., Gatley, I., Wade, R., Duncan, W. D., Garden, R., and Becklin, E. E. 1984, *Ap. J.*, **284**, 118 (Paper I).
Geballe, T. R., Persson, S. E., Lacy, J. H., Neugebauer, G., and Beck, S. C. 1982, in *The Galactic Center*, ed. G. R. Riegler and R. D. Blandford (New York: AIP), p. 60.
Gezari, D. Y., Tresch-Feinberg, R., Fazio, G. G., Hoffman, W. F., Gatley, I., Lamb, G., Shu, P., and McCreight, C. 1985. *Ap. J.*, **299**, 1007.
Hall, D. N. B., Kleinmann, S. G., and Scovilie, N. Z. 1982, *Ap. J. (Letters)*, **262**, L53.
Henry, J. P., DePoy, D. L., and Becklin, E. E. 1984, *Ap. J. (Letters)*, **285**, L27.
Knapp, G. R. 1983, in *Kinematics, Dynamics, and Structure of the Milky Way*, ed. W. L. Shuter (Dordrecht: Reidel), p. 233.
Lacy, J. H., Townes, C. H., Geballe, T. R., and Hollenbach, D. J. 1980, *Ap. J.*, **262**, 120.
Lacy, J. H., Townes, C. H., and Hollenbach, D. J. 1982, *Ap. J.*, **262**, 120.
Lebofsky, M. J., Rieke, G. H., and Tokunaga, A. T. 1982, *Ap. J.*, **263**, 736.
Lo, K. Y., and Claussen, M. J. 1983, *Nature*, **306**, 647.
Morris, M., and Yusef-Zadeh, F. 1987, in *The Galactic Center*, (*AIP Conf. Proc.*, **155**), ed. D. A. Backer (New York: AIP), p. 127.
Ozernoy, L. M. 1984*a*, *Astr. Tsirk.* No. 1342.
———. 1984*b*, *Astr. Tsirk.* No. 1349.
Persson, S. E., Geballe, T. R., McGregor, P. J., Edwards, S., and Lonsdale, C. J. 1984, *Ap. J.*, **286**, 289.
Serabyn, E., and Lacy, J. H. 1985, *Ap. J.*, **293**, 445.
Simon, M., Felli, M., Cassar, L., Fischer, J., and Massi, M. 1983, *Ap. J.*, **266**, 623.
Storey, J. W., and Allen, D. A. 1983, *M.N.R.A.S.*, **204**, 1153.
van Gorkom, J. H., Schwartz, U. J., and Bregman, J. D. 1985, in *IAU Symposium 106, The Milky Way Galaxy*, ed. H. van Woerden *et al.* (Dordrecht: Reidel), p. 317.
Wade, R. 1983, *Proc. Soc. Photo-Opt. Instr. Eng.*, **445**, 47.
Wade, R., Geballe, T. R., Krisciunas, K., Gatley, I., and Bird, M. C. 1987, *Ap. J.*, **320**, 570.
Wynn-Williams, C. G. 1984, in *Galactic and Extragalactic Infrared Spectroscopy*, ed. M. F. Kessler and J. P. Phillips (Dordrecht: Reidel), p. 133.

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