THE ASTROPHYSICAL JOURNAL, 284:118–125, 1984 September 1

OBSERVATIONS OF BROAD HELIUM AND HYDROGEN LINES IN THE VERY CENTER OF THE GALAXY

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Received 1983 November 18; accepted 1984 March 7

ABSTRACT

Measurements of the 2.06 μm 2 ^1P–2 ^1S line of He I and the 4.05 μm Brackett-α line of H I at IRS 16 in the galactic center show that high velocity emission extends to ± 700 km s^{-1} in both lines. A map of Brα spectra demonstrates that this high velocity line emission is concentrated within a few arc seconds of IRS 16. When interpreted as outflow from IRS 16, the broad line emission implies $1 \times 10^{-4} \lesssim \dot{M} \lesssim 3 \times 10^{-2}$ $M_\odot$ yr^{-1}, consistent with that needed to produce the shocked H_2 seen 2 pc distant from IRS 16. IRS 16 or the compact radio source appears to supply the ionizing radiation responsible for the line emission in its flow. If in addition it ionizes the rest of the helium observed at 2.06 μm in its vicinity, its Lyman continuum emission is probably the dominant fraction of that required to ionize all of Sgr A West. Absence of He I 5–4 lines in the Brα spectrum of IRS 16 precludes an extreme overabundance of helium and, together with analysis of 2.06 μm line formation in an outflowing wind, suggests that He/H is near normal.

Subject headings: abundances — galaxies: Milky Way — galaxies: nuclei — infrared: spectra — line profiles

I. INTRODUCTION

It has been known for some time that the center of the Galaxy contains an unusual infrared object, IRS 16, which lies at the center of the nuclear stellar mass distribution (Becklin and Neugebauer 1975) and is very nearly coincident with a unique compact, nonthermal radio object (Balick and Brown 1974) with which it may be associated. Two fundamental question concerning these objects are (1) what are their physical natures and (2) to what extent do they determine the interstellar environment of the central few cubic parsecs of the Galaxy. Despite intense study of both IRS 16 and the compact radio source, the first question remains unanswered. The second question has been discussed in some detail (e.g., Lacy, Townes, and Hollenbach 1982; Townes *et al.* 1983), but until very recently no direct evidence linking IRS 16 to other activity in the galactic center was available.

Recently, Hall, Kleinmann, and Scoville (1982) have reported that the width of the 2 ^1P–2 ^1S helium line at 2.06 μm in the direction of IRS 16 is $\sim$1500 km s^{-1} (FWHM), far greater than had been seen in any other line or location in the galactic center region. In addition, Gatley *et al.* (1984; see also Gatley 1983) have detected line emission from shocked molecular hydrogen in the galactic center, originating $\sim$2 pc distant from the nucleus in cool gas which surrounds the central ionized region. The relative intensities of the H_2 lines they observed imply collisional excitation and suggest as the source of the excitation the impact of a powerful wind on the inner surface of the molecular cloud. Gatley *et al.* propose IRS 16 as the source of the wind. Interpreting the 2.06 μm helium line width as due to high-velocity gas outflow from IRS 16, Gatley *et al.* estimate that a mass loss rate of $\sim 3 \times 10^{-3}$ $M_\odot$ yr^{-1} at a velocity of 750 km s^{-1} is needed to produce the total H_2 line intensity. However, it has not been possible previously to obtain a reliable estimate of the mass flow rate from the vicinity of IRS 16 from this helium line, not only because of the peculiarities of this line (see, e.g., Thompson and Tokunaga 1980) but also because of a lack of spatial information concerning the line at IRS 16, a previous inability to detect equally broad wings in hydrogen lines such as Brγ and Brα from IRS 16 (Hall, Kleinmann, and Scoville 1982; Geballe *et al.* 1982), and associated uncertainty in the helium to hydrogen ratio in IRS 16. Hall, Kleinmann, and Scoville (1982) have suggested from their helium and Brγ line observations that helium is overabundant in IRS 16 by a factor of $\gtrsim$500.

We have remeasured the helium 2.06 μm and hydrogen Brα 4.05 μm line profiles at IRS 16 and have obtained spectra of these lines and Brγ (2.17 μm) on two-dimensional grids of positions centered on IRS 16. The observations and results are presented in §§ II and III, below. In brief, the presence of an unusually broad helium line at IRS 16 was confirmed and allows an improved estimate of its width. Similarly broad wings in the Brα line from IRS 16 were found, and the apparent absence of He I 5–4 line emission implies that helium is not highly overabundant. The spatial grid of Brα spectra shows that the high-velocity line emission is centered at IRS 16. In § IV we estimate a mass flow rate for IRS 16, analyze the formation of the 2.06 μm helium line and its implication for IRS 16 as a source of ionizing photons, and discuss our conclusions regarding IRS 16 in view of current models of the galactic nucleus.

II. OBSERVATIONS

The measurements of the helium and Brα lines were made on the nights of 1983 May 5–8 and June 30–July 2 at the United Kingdom Infrared Telescope (UKIRT) on Mauna Kea using its seven channel 1–5 μm cooled grating spectrometer (Wade 1983). The instrument contains back-to-back gratings used in a Littrow configuration, and a 30° off-axis parabolic mirror as the collimator/camera. The grating turntable, entrance aperture wheel, and blocking filter wheel are driven by stepper motors which are controlled by computer. The InSb detectors each have 0.2 mm square cross sections and are spaced by 0.23 mm. A lens in front of the array converts the f/4 focal ratio of

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the spectrometer to f/2. A 300 line mm^{-1} grating provides a resolution (FWHM) of ~ 550 km s^{-1} at 4.05 μm; a 633 line mm^{-1} grating provides a resolution of ~ 500 km s^{-1} at 2.06 μm.

During the May observations a 3″.6 diameter (FWHM) beam and a 50″ chop (EW) were employed to observe the helium line at IRS 16 and at positions roughly 4″ east, west, south, and northeast of it. Spectra of Brγ also were obtained at most of these positions. The broad helium line found by Hall, Kleinmann, and Scoville (1982) at IRS 16 was confirmed, but no clear evidence for a broad Brγ line was found. The helium line also was detected at all four surrounding positions. Following improvements to the spectrometer, a new spectrum of the helium line at IRS 16 was obtained on June 30 using a 4″.2 diameter (FWHM) beam and a 50″ EW chop and is shown in Figure 1. On July 1 spectra of Brα at IRS 16 revealed the presence of faint high-velocity wings. Subsequently a 14 position grid of Brα spectra, centered on IRS 16 was obtained on July 2, and is shown in Figure 2. The observed characteristics of the Brα line in each of these spectra are given in Table 1. The Brα spectrum in the central position is also reproduced in Figure 1. The latter beam diameter and chop also were used for these measurements. Adjacent positions in the grid are separated by 4″. Combined relative pointing and guiding errors are throught to be less than 1″ at each position. During the June–July observations the helium and Brα lines each were measured at three grating angles chosen so that each spectrum was evenly sampled every one-third of a resolution element within 1000 km s^{-1} of line center. The response of the instrument to an unresolved line (the Brα line in the planetary nebula NGC 6572) is shown in Figure 1 and in the lower left-hand panel of Figure 2. Frequency calibration was obtained from this spectrum and from the 2.06 μm helium line in NGC 6210. The accuracies of the velocity scales in Figures 1 and 2 are better than 1000 km s^{-1}.

IRS 16 was found at 2.06 μm by offsetting from IRS 7 and then peaking the signal; the offset was found to be 1″.3 east and

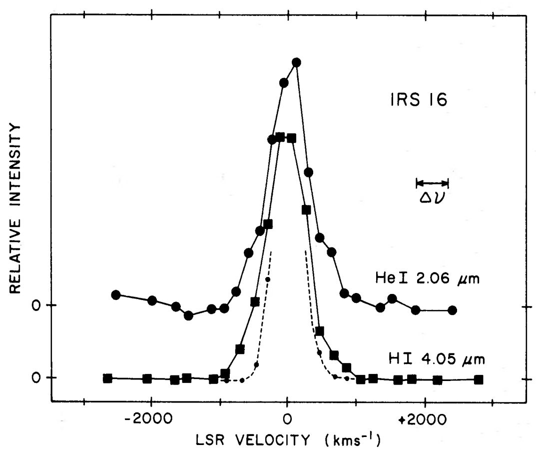

FIG. 1.—Spectra of H I Brα at 4.05 μm (*lower*) and the 2 ^1P–2 ^1S line of He I at 2.06 μm (*upper*) in IRS 16. The spectra are placed on the same velocity scale and normalized to the same peak intensity. A linear baseline was subtracted from the observed helium spectrum, and a flat baseline was subtracted from the Brα spectrum. The instrumental FWHM (approximately the same for each spectrum) is shown, as are the wings of the profile of the unresolved Brα line in NGC 6572 (*dashed line*), scaled to the same peak intensity as IRS 16 Brα. The noise in each spectrum may be judged from the fluctuations in the baseline.

TABLE 1

OBSERVED BRACKETT-α LINE PARAMETERS

Location	Flux[a] (10^{-19} W cm^{-2})	FWHM[b] (km s^{-1})	Observed Velocity Range[c] (km s^{-1})	Estimated Actual Velocity Range[d] (km s^{-1})
NGC 6572	...	600	1350	(50)
IRS 16	9.2	700	2100	1400
4″E	7.7	600	1500	300
4″W	6.8	800	1900[e]	1000[e]
4″N	1.6	700	[e]	[e]
4″S	7.8	700	1850	900
4″N, 4″E	7.1	600	1450	200
4″N, 4″W	1.9	700	1750[e]	<200
4″S, 4″E	5.4	600	1450	200
4″S, 4″W	10.0	700	1750	700
8″E	2.5	600	1350	<200
8″W	5.3	600	1350	<200
8″N	1.0	[e]	[e]	[e]
8″S	2.3	700	1550	400
2″W	9.7	750	2100	1400

[a] In the 4″.2 beam; uncertainties are ±15%; corrected for an assumed $\mathrm{He}^+/\mathrm{H}^+ = 0.1$.
[b] Not deconvolved; uncertainties are typically ±50 km s^{-1}.
[c] Not deconvolved; uncertainties are typically ±100 km s^{-1}.
[d] Deconvolved; uncertainties typically 200 km s^{-1} or less.
[e] Uncertainty is substantially larger than its typical value.

6″.1 south. At 4.05 μm no peaking was used on IRS 16; instead, the above offset was used to define the central point of the grid. The total integration time for the 2.06 μm spectrum was 63 minutes. The integration time for each Brα spectrum was 8 minutes, with the exception of the central IRS 16 spectrum which was observed for a total of 24 minutes. Each spectrum has been ratioed by that of the nearby bright standard BS 6616 or BS 7063 divided by the appropriate temperature blackbody spectrum in order to remove instrumental and atmospheric transmission. By comparison with BS 7063, BS 6616 was observed to have a weak Brα absorption; a small correction was applied when it was used. The noise in each spectrum may be estimated by fluctuations in the baseline. The large fluctuations in the Brα spectra taken 8″ north and 4″ west of IRS 16 are probably due to the presence of bright point sources (IRS 7 and IRS 3, respectively) near the edge of the beam.

The atmospheric transmission near Brα and Brγ, as viewed by the grating spectrometer, is flat. Near the helium line at 2.06 μm the transmission varies with wavelength due to the line's proximity to the center of a strong telluric vibration-rotation band of CO_2. When observed at higher spectral resolution, the lines in this band are opaque, have equivalent widths of about 20 km s^{-1}, and are roughly evenly spaced by ~ 100 km s^{-1}. Unless there are prominent structures in the helium line profile in these 20 km s^{-1} wide intervals, the CO_2 band will not affect the shape of the helium line as viewed at the present spectral resolution, and flux calibration should be reasonably accurate.

III. RESULTS

a) The Spectra at IRS 16

Figure 1 clearly shows that both the helium 2.06 μm and hydrogen Brα lines are unusually broad at the position of IRS 16. The quality of the data is such that line emission can be detected to 3% of the peak intensity in Brα, and approximately twice that in the helium line. The observed full width at the 3% level of Brα is 2100 km s^{-1}. However, the instrumental profile

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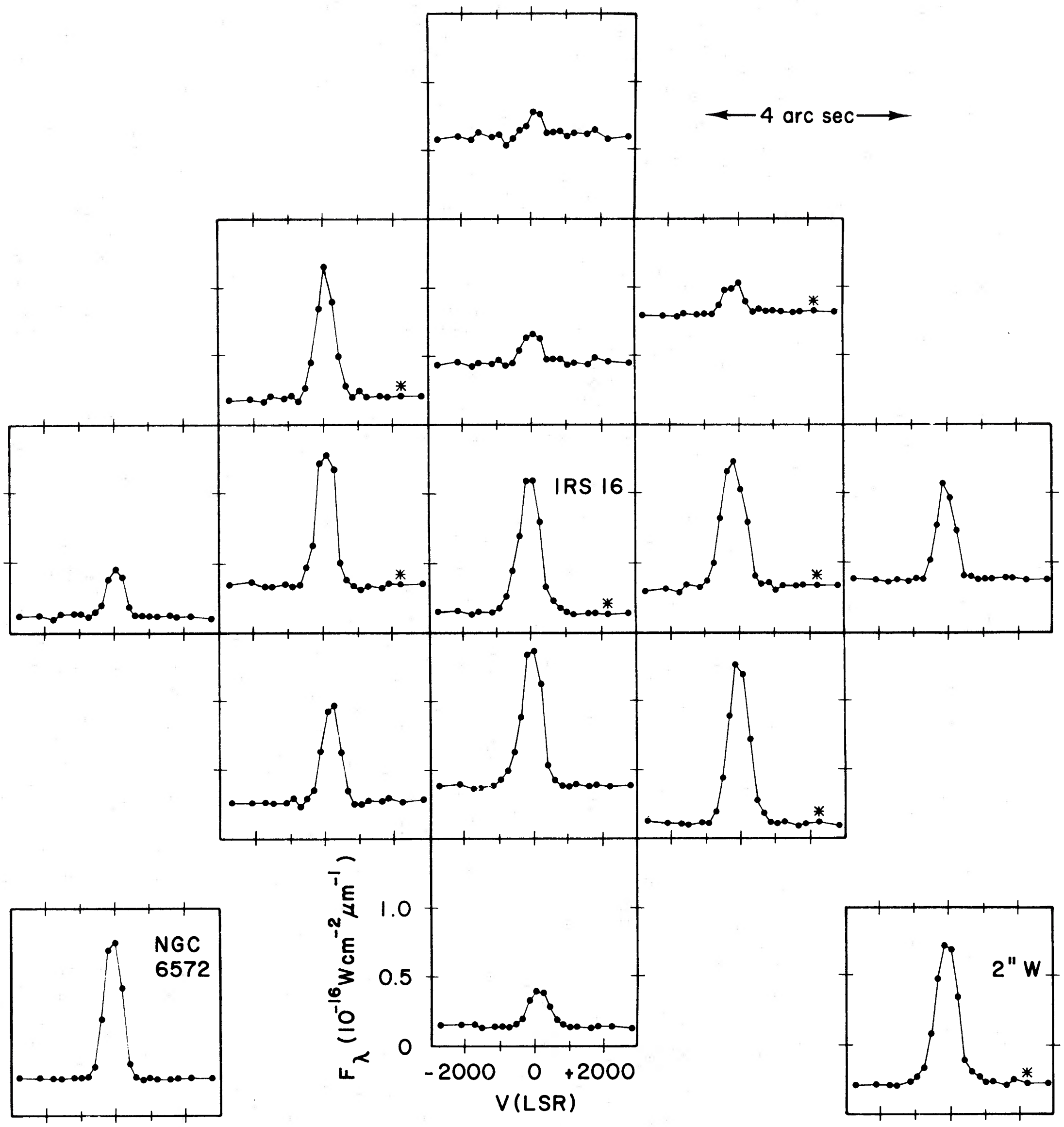

FIG. 2.—Spectra of Brα near IRS 16 observed with a 4"2 beam. The 13 uppermost spectra are arranged according to position on the sky. North is up, east is to the left, and the separation of neighboring spectra is 4". The velocity scale is given on the spectrum of NGC 6572 at lower left and indicated on the other spectra; an intensity scale is given on the lower middle spectrum. A spectrum taken 2" west of IRS 16 is shown at lower right. An asterisk by a spectrum indicates that a continuum level of 0.5×10^{-16} W cm^{-2} μm^{-1} has been subtracted.

is responsible for a significant fraction of the observed line width. The data are most consistent with a minimum intrinsic full width at zero intensity (FWZI) of Brα of 1400 ± 200 km s^{-1}; larger values of FWZI being consistent only with line emission which is too weak to be detected in the present experiment. The same value of FWZI is implied for the helium line, although with somewhat higher uncertainty due to the lower signal-to-noise ratio. The full extent of the helium line is thus considerably less than Hall, Kleinmann, and Scoville's (1982) reported value of 3000 km s^{-1}, which was based on a higher resolution, but lower signal-to-noise spectrum. Hall, Kleinmann, and Scoville (1982) had also reported a marginally significant redshift for the helium line of +300 km s^{-1}. In the present spectrum the peaks of both the helium and Brα lines appear unshifted to within 100 km s^{-1}.

It is immediately apparent from Figure 1 that the helium 2.06 μm line is composed of a narrow unresolved component and a broad component. Comparison of the Brα spectrum with the instrumental profile suggests the same interpretation for it, because the observed FWHMs of the Brα line in NGC 6572 and IRS 16 are approximately equal, but the total velocity extents of the lines differ greatly (see Fig. 1). However, it is obvious that the broad component present in Brα must be relatively much weaker than in the helium line. In order to further demonstrate and quantify these conclusions, a deconvolution routine, described by Lucy (1975), was applied to an ideal (noiseless) version of the data. The results confirm the above value of the FWZI and indicate that at IRS 16 perhaps 40% of the total helium line flux is due to the broad component, whereas only about 20% of the Brα flux is in the broad component.

The He I 5–4 transition can be used to test the abundance ratio, He/H $\gtrsim 50$, suggested by Hall, Kleinmann, and Scoville (1982) for the high-velocity material. Several components of

He I 5–4 (Martin 1973) lie within the Brα scan and two of them, both shifted by -240 km s^{-1} with respect to Brα, together contain approximately half of the total He I 5–4 intensity. Their combined line emission thus should be about one-twentieth the strength of Brα if He^+/H^+ = He/H is normal. A velocity shift in the broad component of Brα should be readily apparent if helium is greatly overabundant. In addition, other weaker He I 5–4 lines which occur approximately at -1100, -800, $+150$, and $+300$ km s^{-1} relative to Brα, would be seen. The contribution of the He II 10–8 line at 4.05 μm also should be small because of the low ionization state of the gas in the galactic center (see below). In Figure 1 the smoothness and symmetry of the entire Brα profile and the apparent lack of a velocity shift of the centroid of the broad wings are consistent with a normal abundance of helium and imply that helium is not overabundant by more than about a factor of 5 (He/H < 0.5). Therefore, in the balance of this paper we assume that the 4.05 μm emission profiles are predominantly due to hydrogen Brα.

b) The Brα Map

Close inspection of Figure 2 or examination of Table 1 demonstrates that the broad wings on the Brα line are localized near IRS 16. The strengths of the wings and the FWZI of the line decrease in all directions away from the position of the central spectrum of the grid. To the north and east of the central position the decrease is very rapid. For example, deconvolution of the spectrum taken 4″ east of the central position shows essentially no emission beyond ± 200 km s^{-1} from $v_{LSR} = 0$ apart from that which can be ascribed to the strongest component of He I 5–4 assuming a near normal abundance of helium. Four arcsec south of the center, however, the velocity extent and strength of the blue wing remain at the same level, although the red wing is decreased in both strength and extent. Both wings are only somewhat less broad to the southwest of IRS 16. The 4″ west spectrum is somewhat ambiguous; however, at 2″ west (the approximate location of the compact radio source, according to the position given in Storey and Allen 1983) both wings appear to be as strong and extensive as in the central position. Further to the south and west, the decrease in wing strength and extent is rapid. Thus, the observations are consistent with the centroid of the high velocity Brα emission lying approximately 1″ west and 1″ south of the central position of the grid, which corresponds within the uncertainties to both IRS 16 and the nonthermal radio source. In §§ IV and V we refer to both objects collectively as IRS 16. The observations also suggest the possibility that the high-velocity emission is extended over a few arc seconds. Higher angular resolution is required to better test this possibility and to determine the location of the centroid more accurately.

Previous Brα grating spectroscopy of IRS 16 by Geballe *et al.* (1982) failed to detect the broad wings seen in the present spectra. The reasons for this are twofold: the 8″ aperture previously used diluted the broad component relative to the narrow component of the line, and the new instrument has higher sensitivity both due to its employment of a detector array and its use on Mauna Kea. The faintness of the Brα broad wings relative to those of the 2.06 μm He I line probably explains why they were not detected in Brγ by Hall, Kleinmann, and Scoville (1982) or by us in the 1983 May spectra. The only previous line observations with angular resolution and spatial coverage similar to the present work (but not similar in velocity resolution or coverage) are the Ne II 12.8 μm line measurements of Lacy *et al.* (1980). The distribution of Brα line intensities in the present data is similar to that of the Ne II data.

TABLE 2

OBSERVED HELIUM AND BRACKETT-γ LINE FLUXES

Location	Beam Diameter (arcsec)	2.06 μm Helium Line Flux (10^{-20} W cm^{-2})	2.17 μm Brγ Line Flux (10^{-20} W cm^{-2})
IRS 16	4.2	3.1 ± 0.5	...
IRS 16	3.6	2.4 ± 0.4	2.9 ± 0.6
4″E	3.6	2.3 ± 0.5	3.8 ± 0.6
4″W	3.6	1.5 ± 0.5	2.3 ± 0.6
4″S	3.6	1.8 ± 0.5	3.6 ± 0.6
2″E, 3″5N ...	3.6	1.2 ± 0.5	...

c) Helium and Brγ Line Observations

The helium lines observed at positions 4″ east and south of IRS 16 are roughly comparable in intensity to that observed at IRS 16. The intensities 4″ west and northeast of IRS 16 are somewhat lower. Table 2 gives the observed fluxes at these positions, both for the helium line and for Brγ. The ratio of the helium and Brγ line intensities is highest at IRS 16. Except for the helium line spectrum at IRS 16, the signal-to-noise ratios obtained are insufficient to specify the widths of these lines; however, none of the lines appears broader than at IRS 16.

d) Line Fluxes and Extinction toward IRS 16

The observed hydrogen Brα line flux in the 4″2 beam is 9.2×10^{-19} W cm^{-2} after subtraction of a small contribution from He I 5–4 which assumes a normal helium abundance. The total measured helium 2.06 μm line flux in the 4″2 beam at IRS 16 is 3.1×10^{-20} W cm^{-2}, with an estimated uncertainty of ± 15%. This measurement as well as the earlier one with a 3″6 beam, although consistent with the Hall, Kleinmann, and Scoville (1982) value of $2.2 \pm 0.3 \times 10^{-20}$ W cm^{-2} in a 3″8 beam, gives a slightly higher line surface brightness. A more markedly higher Brγ surface brightness at IRS 16 than those derived from the measurements of the Wollman, Smith, and Larson (1982) and Hall, Kleinmann, and Scoville (1982) is obtained from the present measurement. In addition, the IRS 16 continuum flux densities at 2 μm and 4 μm, as determined from the present spectra, are somewhat higher than those interpolated from the Becklin *et al.* (1978) photometry. However, elsewhere (e.g., IRS 1) the various continuum and line measurements are more consistent. Because of the location of IRS 16 on a strong north-south gradient of infrared continuum and line emission, small ($\sim 1''$) differences in pointing easily could account for the discrepancies there.

The reddening correction for the ionized gas near IRS 16 may be determined from the Brα and Brγ line fluxes in Tables 1 and 2. Assuming low-density, case B recombination theory with $T_e \sim 7500$ K and correcting for beam size effects, the 2.17–4.05 μm reddenings obtained are 2.2 ± 0.5 mag toward IRS 16 and the position 4″ west, and 1.7 ± 0.4 mag toward the positions 4″ east and south. Although the uncertainties are large, there is some indication of higher than typical reddening both toward IRS 16 and to the west. For comparison, the value interpolated from the Becklin *et al.* (1978) average extinction curve to infrared continuum sources in the galactic center is about 1.6 mag.

In order to have dereddened helium and Brα line fluxes at IRS 16 for use in the discussion to follow, we assume extinctions of 1.0 mag at 4.05 μm, 2.9 mag at 2.17 μm, and 3.2 mag at 2.06 μm. These values are close to those interpolated from the Becklin *et al.* (1978) data but represent a compromise with the present results. The extinction-corrected fluxes in the 4".2 beam are then 2.3×10^{-18} W cm^{-2} for the Brα line and 6.0×10^{-19} W cm^{-2} for the helium line. Therefore, the corrected fluxes in the broad line component at IRS 16 are 4.6×10^{-19} W cm^{-2} in Brα and 2.4×10^{-19} W cm^{-2} in the helium line.

IV. DISCUSSION

a) The Line Width and an Estimate of the Mass Loss Rate

Both the 2.06 μm He I and 4.05 μm H I line profiles at IRS 16 have been shown to be a superposition of narrow and broad components. The narrow component previously has been found to be emitted by ionized clouds in the galactic center, with velocities $|v| < 300$ km s^{-1}, which overlap our line of sight to IRS 16 (Geballe *et al.* 1982); it will not be discussed further here. The present data demonstrate that unlike the narrow component, the broad component is localized at IRS 16. The importance of the detection and accurate measurement of the broad hydrogen line emission is that its profile implies a dominant abundance of hydrogen over helium in the high-velocity gas and therefore permits meaningful estimates of ionization and mass flow parameters to be made for IRS 16.

The cause of the high velocities at IRS 16 cannot be thermal broadening because the hydrogen and helium line widths are equal. Turbulent motions are also ruled out by the detectable presence of the helium line, because efficient resonant scattering of the He 2 ^1P–1 ^1S 584 Å photons would not be possible under such conditions (see Thompson and Tokunaga 1980, and § IV*b*, below). This leaves organized gas motions as the likely cause. The present measurements cannot distinguish between circular or radial motions of the ionized gas. We note that the observed high velocities agree well with predicted orbital velocities within 2" of a central $3 \times 10^6\ M_\odot$ pointlike mass, which has been suggested to be present in the galactic center by Lacy *et al.* (1980). However, we will discuss the present spectra in terms of a radial outflow from IRS 16 for the following reasons: (1) The morphology of the gas in the galactic nucleus, which consists most simply of a central, largely low-density ionized region of diameter $\sim$4 pc surrounded by higher density cooler material, suggests that a radial momentum agent is responsible for clearing out the center; that agent cannot be the luminosity of individual stars (Gatley *et al.* 1984). (2) The observed presence of collisionally shocked H_2 at the boundary of the low- and high-density regions implies the impact of material, originating from a roughly central position in the nucleus, upon the higher density surrounding cloud. Therefore, an outflow from IRS 16 should be seriously considered.

For the case of a constant velocity outflow and with the assumption that the outer radius of the ionized flow is much greater than the inner radius, Simon *et al.* (1983) have derived formulae relating the inner radius, the flow speed, and the mass loss rate to the Brα line flux. In the present case a reasonable lower limit to the inner radius is the radius of an optically thick surface at 10^4 K which emits the observed broad Brα line flux density; this radius is $\sim 2.5 \times 10^{13}$ cm. Then, from Simon *et al.* (1983) equation (16) for an optically thin line and using $D = 8.5$ kpc (Gunn, Knapp, and Tremaine 1979) and $v = 700$ km s^{-1}, $\dot{M} > 3 \times 10^{-5}\ M_\odot$ yr^{-1}. A self-consistency check using their equation (10) yields $\tau < 0.3$. For larger inner radii, r_i, $\dot{M}$ varies as $r_i^{1/2}$ and τ as r_i^{-2}. The maximum r_i permitted by the measurements corresponds roughly to half the aperture radius, so that the high-velocity emission be only partially spatially resolved at the present angular resolution; in this case, from equation (16), $\dot{M} = 3 \times 10^{-3}\ M_\odot$ yr^{-1}. Because (1) Simon *et al.* have assumed a pure hydrogen flow, (2) the total Brα line flux may be larger than that observed in the central position, and (3) variation of flow speed with radius can increase $\dot{M}$ for a given line flux, the mass flow rate probably lies in the range $10^{-4}\ M_\odot$ yr$^{-1} < \dot{M} < 3 \times 10^{-2}\ M_\odot$ yr^{-1}. Gatley *et al.*'s (1984) requirement for producing their observed H_2 $S(1)$ line intensity corresponds to an isotropic mass loss rate of $\sim 3 \times 10^{-3}\ M_\odot$ yr^{-1} at the observed velocity of 700 km s^{-1}. This value of $\dot{M}$ lies well within the above range.

The larger mass loss rates in the above range require that the observable line-emitting region has a characteristic size no smaller than about 1'. An object or objects of this size, with near-infrared colors bluer than their surroundings, have been observed at IRS 16 by Storey and Allen (1983; see also Becklin and Neugebauer 1975). However, the free-free and free-bound emission corresponding to the Brα broad line flux provides only a few percent of the 1.65 μm and 2.2 μm intensities of IRS 16. It appears likely that this blue emission from IRS 16 is continuum radiation from the Rayleigh-Jeans tail of a hot and luminous object.

b) Helium 2.06 Micron Line Enhancement

Strong line emission from the 2.06 μm 2 ^1P–2 ^1S transition of neutral helium has been observed in a wide variety of ionized regions (e.g., see Treffers *et al.* 1976; Wynn-Williams *et al.* 1978; Thompson and Tokunaga 1980). The first and last groups of authors conclude that this helium line is observable only when the heavily favored 2 ^1P–1 ^1S transition at 584 Å is very optically thick. Thompson and Tokunaga conclude in addition that the 2.06 μm line strength is limited by photoionization of hydrogen by the 584 Å photons. Following their discussion, the approximate relation given below can be used to estimate the enhancement of this line:

$$F \approx (n_{\mathrm{He}^+}\, n_e\, \alpha_{2\,^1P}) \left(\frac{10^{-3} + 10^{-3} P_s/P_i}{1 + 10^{-3} P_s/P_i} \right) . \qquad (1)$$

Here F is the line strength, and n_e and n_{He^+} are the free electron and singly ionized helium densities, $\alpha_{2\,^1P}$ the rate of population of the 2 ^1P level (same dimensions as an effective recombination coefficient), 10^{-3} is the branching ratio of the 2.06 μm transition from this level, P_s is the probability that the 2 ^1P–1 ^1S 584 Å photon is resonantly scattered off of neutral helium, and P_i is the probability that the same photon ionizes hydrogen. It is assumed that the probability that the ultraviolet photon is absorbed by dust or escapes the H II region is much less than either P_s or P_i. At 10^4 K the ratio of these probabilities *in a localized part of the* H II *region* can be expressed as follows:

$$\frac{P_s}{P_i} \approx \frac{\sigma_s n_{\mathrm{He}^\circ}}{\sigma_i n_{\mathrm{H}^\circ}} \approx 2 \times 10^4 e^{-[(v_s + \Delta v)/6]^2} \frac{n_{\mathrm{He}^\circ}}{n_{\mathrm{H}^\circ}} , \qquad (2)$$

where σ_s and σ_i are the cross sections for the above processes (values from Thompson and Tokunaga 1980), v_s is the shift (in km s^{-1}) of the average velocity of the gas at a distance of one mean free path which a 584 Å photon would have in a stationary H II region, Δv is the shift (in km s^{-1}) of the photon from local line center, and n_{He° and n_{H° are the densities of neutral helium and hydrogen. The thermal velocity dispersion of helium at 10^4 K is 6 km s^{-1}.

An important difference between this analysis and that of Thompson and Tokunaga is that they used a helium to hydrogen ratio of 1/10 in discussing enhancement of the 2.06 μm line, whereas in equation (2) the ratio of *neutral* helium to *neutral* hydrogen is the relevant parameter. In the He$^+$ zone, where the 2.06 μm line arises, the latter ratio can vary greatly with position, and in places can be as large as 10^3, although He/H is normal (see, e.g., Rubin 1968 or Osterbrock 1974). When all other effects are constant and as long as He$^+$ is abundant, the 2.06 μm line will originate predominantly from portions of the H II region where $n_{\mathrm{He}^\circ}/n_{\mathrm{H}^\circ}$ is either largest or large enough to make $10^{-3}P_s/P_i \gg 1$. In the latter locations it is likely that every recombination to the 2 ^1P level will ultimately result in a 2.06 μm photon; the line emission will not be limited by ionization of hydrogen.

Population of the 2 ^1P level can proceed not only by radiative recombination of singlet levels but also by transfer of 2 ^3S state atoms by electron collisions, which has a comparable rate at $n_e \gtrsim n_c = 3 \times 10^3$ cm^{-3} and $T \sim 10^4$ K (see Osterbrock 1974). Using the line ratios in Brocklehurst (1971) and Giles (1977), one can estimate the maximum ratio of the helium line to nearby Brγ. At 10^4 K and when $10^{-3}P_s/P_i \gg 1$, the ratio is $10n_{\mathrm{He}^+}/n_{\mathrm{H}^+}$ for $n_e \ll n_c$ and $20n_{\mathrm{He}^+}/n_{\mathrm{H}^+}$ for $n_e \gg n_c$. The emission measure derived from the present data implies $n_e \gg n_c$ over most or all of the broad line region (see below). Therefore if the above conditions are satisfied and if the emission occurs entirely within the He$^+$ zone with $n_{\mathrm{He}^+}/n_{\mathrm{H}^+} \approx \mathrm{He/H} \approx 0.1$, the broad component of the helium line will be twice as intense as the broad component of Brγ. Hall, Kleinmann, and Scoville (1982) and we have found that at IRS 16 the total helium and Brγ intensities are roughly equal, in which case, assuming that the Brγ profile is similar to Brα, the intensities of the broad components are indeed in the above ratio. This is a further indication that He/H cannot be far from the cosmic value in the broad line region.

For cool ionizing sources ($T \lesssim 35{,}000$ K), the 2.06 μm line emitting region will surround the ionizing source but be well within the H II region; thus, the total helium 2.06 μm line intensity of the H II region will be much less than the total Brγ intensity. For hotter sources, which produce nearly coincident He$^+$ and H$^+$ zones, Thompson and Tokunaga's analysis will apply; the helium line emission will be approximately uniform out to the H$^+$ Strömgren radius, and its total intensity can approach or surpass Brγ. The ionizing source(s) in the galactic center are known to be cool (Lacy *et al.* 1980), and the present observations show that the helium line to Brγ line ratio is strongest at IRS 16. Because of this and the spatial coincidences of both the compact radio source and the broad lines with IRS 16, we infer that IRS 16 contains a source of ionizing photons.

Additional factors affecting the resonant scattering probability are Δv and v_s in equation (2). Hall, Kleinmann, and Scoville (1982) apparently invoked these factors in arguing that the presence of such a broad helium line must imply an extreme overabundance of helium. However, if the observed line width is due to organized mass motion, as we believe and as also was argued by Wollman, Smith, and Larson (1982), then locally Δv will be much less than the observed line width and more comparable to the thermal line width. In addition, if the mass loss rate is in the above range and if the abundance of neutral helium is sufficiently high, v_s will be negligibly small over a 584 Å photon mean free path, for any reasonable $v(r)$. For example, with a mass loss rate of 10^{-3} $M_\odot$ yr^{-1}, a constant radial outflow velocity of 700 km s^{-1}, a normal helium abundance, and the absorption cross section given by Thompson and Tokunaga, $f > 10^{-21}r$ is required for photons emitted tangentially, where f is the fractional abundance of neutral helium and r is the distance from the source in centimeters. Thus, even at $r = 10^{18}$ cm, only $f > 10^{-3}$ is required to maintain an acceptably high scattering probability. Similar results are obtained for $v(r) \propto r^a$; $|a| \leq 1$. It should be noted that a strong 2.06 μm helium line was observed in Nova Cygni 1975 (Grasdalen and Joyce 1976; Strittmatter *et al.* 1977), whose ejecta had a normal value of He/H (Ferland 1978).

c) *The Ionizing Luminosity of IRS 16*

We have concluded in the previous section that IRS 16 is a source of ionizing photons, at least some of which excite the H and He in its high-velocity flow and lead to emission of the broad Brα and 2.06 μm lines. Because various models for the ionization of the galactic center, both involving groups of hot stars and a single ionizing source, have been proposed (e.g., Lacy, Townes, and Hollenbach 1982; Lebofsky, Rieke, and Tokunaga 1982; Gatley *et al.* 1984), it is important to compare the Lyman continuum emission required to ionize the flow which is originating at IRS 16, and that required by the total helium line emission from the region around IRS 16, to that of Sgr A West as a whole. The latter is thought to be $\sim 4 \times 10^{50}$ Lyman continuum photons per second (Lacy, Townes, and Hollenbach 1982).

First, consider just the flow. From the dereddened strength of the broad Brα component at the IRS 16 position alone a volume emission measure, $(n_e^2V)_{\mathrm{H}} \sim 3 \times 10^{60}$ cm^{-3} is derived for the high-velocity ionized gas in the central 4".2 beam. The rate of production of Lyman continuum photons which produces this emission measure, $\sim 1 \times 10^{48}$ s^{-1}, corresponds approximately to that of a single O9.5 ZAMS star, or ~ 0.25% of the ionization of Sgr A West. The total amount of broad Brα emission observed at all positions corresponds to perhaps twice this. The volume emission measure derived from the broad helium component cannot be greater than the emission measure calculated from broad Brα, because the helium line only can originate from an equal or smaller volume. From the dereddened strength of the broad helium component at IRS 16 we obtain (following the notation of Hall, Kleinmann, and Scoville 1982):

$$(n_e^2V)_{\mathrm{H}} \sim q\left(\frac{6 \times 10^{59}}{f_e}\right)\left(\frac{\beta + 1}{\beta}\right),$$

where $\frac{1}{2} \lesssim q < 1$ indicates the contribution of collisional transfer of 2 ^3S atoms to the 2 ^1P level population, f_e is the fraction of all excitations to the 2 ^1P level which result in 2.06 μm line emission and $\beta = \mathrm{He}^+/\mathrm{H}^+$. We as well as Thompson and Tokunaga (1980) have argued that f_e will be near unity when the helium line is strong. Therefore for a normal abundance of helium the emission measures derived from the broad Brα and helium components at IRS 16 are roughly equal, and hence both broad lines arise in roughly the same volume. In conclusion, the amount of ionizing luminosity corresponding to the broad line emission *alone* ($\sim 2 \times 10^{48}$ photons s^{-1}) is but a small fraction of that required for Sgr A West. *This amount,* *however, is probably only a rather extreme lower limit to the ionizing luminosity of IRS 16.*

The ionizing luminosity of IRS 16 is likely to be substantially higher than the above value for two reasons. The first, already mentioned briefly, is that the ionizing radiation in the galactic center has a low temperature, 30,000 K $< T <$ 35,000 K (Lacy *et al.* 1980). At such temperatures the hydrogen-ionizing photons so vastly outnumber the helium-ionizing photons that the H II region extends well beyond the He^+ zone. In the present case this implies that the H II region ionized by IRS 16 extends well beyond the broad line region, and therefore that the ionizing luminosity implied by the broad helium and hydrogen lines must be scaled up. For example, in an H II region where the exciting star has T_{eff} = 35,000 K, the total number of ionizing photons is about a factor of 5 greater than the number in the He^+ zone where the 2.06 μm line emission arises. If T = 30,000 K the factor is approximately 50 (Rubin 1983; see also Osterbrock 1974, p. 26). Therefore, since the far-ultraviolet spectrum of the IRS 16 ionization source(s) is probably similar to that of stars in the above temperature range, the actual Lyman continuum emission inferred from the flow alone is between 10^{49} and 10^{50} photons per second. Values in this range constitute a significant fraction of the ionizing radiation in Sgr A West.

The second reason that the Lyman continuum emission from IRS 16 may be underestimated is that in addition to ionizing the high-velocity helium, IRS 16 probably ionizes some or all of the rest of the helium observed in its vicinity (Table 2). Only the broad component of the helium and hydrogen lines have been used in the above estimate of the Lyman continuum emission from IRS 16. However, the total observed helium line flux at and around IRS 16 exceeds the broad line flux at IRS 16 by an order of magnitude (see Table 2). If, for example, all of this is attributed to IRS 16, its ionizing luminosity must be increased by another order of magnitude, and IRS 16 almost surely becomes the dominant ionization source in Sgr A West.

The above two arguments taken together imply that essentially all of the ionizing luminosity of Sgr A West arises from within approximately 5″ of IRS 16. The compact radio source or other unusual objects within IRS 16 are the obvious candidates for the origin of this radiation, although a cluster of rather normal hot stars in the central several arc seconds may also contribute. Lacy, Townes, and Hollenbach (1982) have argued that barring exceptional circumstances any source, including a simple accretion disk around a massive black hole, which provided more than about 10% of the ionizing radiation in the galactic center would be brighter at 2.2 μm than any single object in the galactic center except IRS 7, which is known to be a nonionizing source. If the temperature of the ionizing radiation from IRS 16 is ~30,000 K or if IRS 16 ionizes all of the helium observed within about 5″ of it, their argument must be reexamined.

V. CONCLUSION

Because mass loss from the galactic center can explain much of its large-scale appearance, and because the range of rates consistent with the observed broad line emission encompasses the value required by the H_2 line measurements of Gatley *et al.* (1984), we believe that the present results are plausible evidence that the high-velocity gas at IRS 16 is a wind which has blown the observed low-density bubble in the galactic center and is responsible for the collisionally shocked H_2 observed at the boundary of this bubble. Our interpretation of the data also suggests that IRS 16 is producing a significant and perhaps substantial fraction of the ionizing radiation in the galactic center. Thus, IRS 16 may control the interstellar environment throughout much of the galactic center. The width of the broad Brα and helium lines and their spatial concentration into volumes of diameter $\lesssim$4″ limits the mass of IRS 16 to $\lesssim 5 \times 10^6 M_\odot$.

The arguments of § IV are suggestive but rather crude. Detailed modeling of ionization structure and 2.06 μm line formation in an outflowing wind are badly needed, but are beyond the scope of this paper. A critical test of the dominance of IRS 16 as an ionizing source will be more extensive measurements of the helium line strength, particularly at much larger distances from IRS 16. If IRS 16 is the dominant ionization source, the helium line strength should decrease more rapidly with distance from it than the hydrogen and Ne II lines. This apparently is the case for the limited measurements given in Table 2. The same argument applies to the 9.0 μm line of Ar III (ionization threshold 27.6 eV, compared to 24.6 eV for He II, 21.6 eV for Ne II, and 13.6 eV for H II); a new and more sensitive search for Ar III in the vicinity of IRS 16 is needed (see Lacy *et al.* 1979). It is also important to obtain accurate values, of the extinction toward IRS 16 and its vicinity. Other important infrared observations which should be made include (1) measurements of the Brα line at higher angular resolution to attempt to resolve the region of high-velocity emission and narrow the range of acceptable mass loss rates; and (2) higher resolution spectra of these lines at IRS 16, with sufficient signal-to-noise ratios to allow more detailed modeling of the high-velocity flow.

We wish to acknowledge a number of helpful discussions with J. H. Lacy and we thank him, G. Serabyn, and C. H. Townes for reading a preliminary version of the manuscript. We also thank R. H. Rubin for providing data in advance of publication. We are indebted to the referee for his suggestions. We are grateful to the entire staffs of ROE and of UKIRT, and most especially to Anna Lucas, for their support.

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