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A SURVEY OF THE 158 MICRON [C II] FINE-STRUCTURE LINE IN THE CENTRAL 50 PARSECS OF THE GALAXY

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ABSTRACT

We report an extensive velocity resolved survey at 1′ resolution of 158 μm [C II] fine-structure line emission in the central 50 pc of our Galaxy. Spectra were taken toward about 625 positions with a new imaging far-infrared spectrometer on board the NASA Kuiper Airborne Observatory. The [C II] emission, tracing the distribution of dense gas dissociated and partially ionized by far-ultraviolet photons, is strongest toward the rotating circumnuclear disk surrounding Sgr A West. A continuous bridge of [C II] line emission connects the Sgr A complex to the thermal radio filaments in the radio arc 10′ north of the center, thus strongly suggesting a direct physical connection between the two.

Outside of the nuclear region, there is a striking anticorrelation between [C II] intensity and the distribution of dense molecular material. The brightest emission preferentially occurs near the edges of the massive Galactic center molecular clouds. We conclude that these clouds are predominantly ionized by external ultraviolet photons, in part from the Sgr A West region itself and in part from OB stars that have relatively recently formed near the center.

The new data suggest a physical connection between the center and the massive interstellar gas clouds in the surrounding 50 pc. The +50 km s^{-1} molecular cloud, for instance, is very likely located within 10 pc of the center. This cloud and the blueshifted cloud complex associated with the radio arc are probably feeding material into the center of the Galaxy.

Subject headings: galaxies: nuclei — galaxies: The Galaxy — infrared: sources — infrared: spectra

1. INTRODUCTION AND OBSERVATIONS

Within about 10′ (or 23 pc at an assumed distance of 8 kpc; Reid 1989) of Sgr A*, the compact radio source at the dynamical center of the Galaxy, there are several large, ionized, and molecular gas clouds, such as the nonthermal and thermal filaments of the radio arc (Yusef-Zadeh, Morris, & Chance 1984), and the massive +50 km s^{-1} (M – 0.02 – 0.07) and +20 km s^{-1} (M – 0.13 – 0.08) molecular clouds (Güsten, Walmsley, & Pauls 1981). Their nature and relationship to the Galactic center are unclear at present. Are these objects in the Galactic center region? Is there any physical connection between the circumnuclear interstellar material and these highly interesting structures farther out? Is the ionized gas in the radio arc excited by ultraviolet radiation, and if so, are there recently formed massive stars in its vicinity?

To address some of these questions, we have recently begun a program of spectroscopic imaging of several far-infrared emission lines in the center of our Galaxy. We report here the results of a velocity-resolved survey of the 157.7409 μm $^2P_{3/2} \rightarrow {}^2P_{1/2}$ fine-structure line of C^+ in the central 50 pc.

The observations were carried out in 1989 July with the new Max-Planck-Institut für extraterrestrische Physik (MPE)–University of California, Berkeley Far-infrared Imaging Fabry-Perot Interferometer on board the NASA Kuiper Airborne Observatory (KAO). The instrument is described in detail in Poglitsch et al. (1991) and Geis (1991). It presently has two cryogenic scanning Fabry-Perots in front of a 5 × 5 pixel array of stressed Ge:Ga photoconductive detectors (see Stacey et al. 1991a). The observations described below were made with 33 km s^{-1} (FWHM) spectral resolution, with square 40″ pixels, and a pixel-to-pixel separation of 40″. Because of diffraction, the beam shape on the sky, as measured by rastering the array over the planet Saturn, was approximately a circular Gaussian of FWHM 55″ (68″ equivalent disk with a corresponding beam solid angle 8.3×10^{-8} sr). Observations were taken by switching the telescope's secondary at 23 Hz approximately 7′.5 perpendicular to the Galactic plane. The telescope was nodded for the frame centered on Sgr A*. For the other positions, either the left or the right beam was used as reference, depending on which beam would point farther away from the Galactic plane. Contamination from the reference beam should therefore be less than our lowest contour level unless there is a large-scale [C II] emission. For calibration, the array was first internally flat-fielded with hot and cold blackbody loads of known temperature designed to have the same area–solid angle product as the telescope. Absolute intensity calibration including diffraction effects was obtained from measurements of Saturn and the Moon. In this way the instrument-sky coupling factor, i.e., the fraction of the flux falling onto the telescope that actually reaches the entrance aperture of the spectrometer as compared to the flux from the internal blackbody loads, was determined to be 0.7. A gas absorption cell in the optical path to the blackbodies was used for wavelength calibration. The 157.7726 μm line of H_2S (Flaud, Camy-Peyret, & Johns 1983) was within our scan, providing for direct wavelength calibration with a 10 km s^{-1} error of the derived velocities. Continuum was subtracted by fitting a baseline to the blue and red ends of the spectra. As this was the first flight series with the new instrument, we conservatively estimate the absolute uncertainty of our flux measurements as about ±40%. The random

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error in the flux was 4×10^{-15} W m^{-2} in a spectral resolution element. We obtain a peak [C II] flux of 2.2×10^{-13} W m^{-2} toward Sgr A*. For comparison, Genzel et al. (1985) reported 1.6×10^{-13} W m^{-2} in a similar beam with the previous UCB spectrometer. Flux measurements at the same position taken with different pixels of the array usually agree to better than 10%, although a few detectors showed larger deviations, probably due to high gain and consequent nonlinearities in the detector electronics. All 25 detectors were operational.

2. RESULTS

We took spectra at 25 different settings of the telescope, resulting in 625 individual spectra. We covered a continuous region $\approx 20' \times 10'$ ($\Delta l \times \Delta b$) in area around the Sgr A complex with good sampling (0.5 to 1 beam spacing). Figure 1 shows an example of the data, a 4 minute integration centered on Sgr A*. Figure 2 gives the resulting velocity channel maps in steps of 30 km s^{-1} (one spectral resolution element). These data are discussed in more detail below.

In addition we took spectra toward the straight, mostly nonthermal filaments of the radio arc. No detectable [C II] emission was seen to be associated with the southern, purely nonthermal part of the straight filaments (G0.16−0.15). [C II] emission centered at $v_{\rm LSR} \approx$ 30–40 km s^{-1} is clearly associated with the thermal source G0.18−0.04 near the middle section of the straight filaments. The strongest [C II] emission ($\approx 6 \times 10^{-4}$ ergs s^{-1} cm^{-2} sr^{-1}) occurs just north and east of the sickle-shaped, thermal arch of G0.18−0.04, at the interface to a dense molecular cloud ($v_{\rm LSR} \approx 25$ km s^{-1}) found by Serabyn & Güsten (1990). Moderately strong emission at velocities near 0 km s^{-1} was found toward the northern end of the straight filaments, at the intersection with the thermal, curved filaments of the "bridge." The bridge itself was not observed

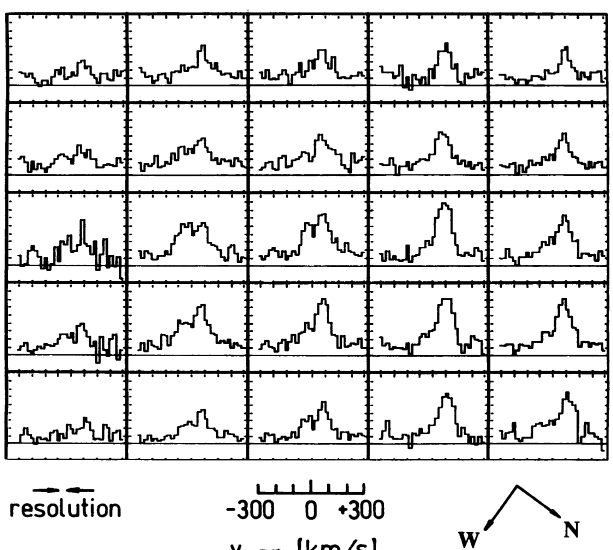

FIG. 1.—[C II] spectra (158 μm $^2P_{3/2} \rightarrow {}^2P_{1/2}$) toward the central 2:5 of the Galaxy, taken with the imaging Fabry-Perot spectrometer FIFI onboard the Kuiper Airborne Observatory. North is toward the lower right, and east is toward the upper right corner pixel. Sgr A* is toward the central pixel, and the pixel-to-pixel separation is 40". The FWHM beam size is 55". Velocity resolution is 33 km s^{-1}, and the spectral scans range from −300 to +300 km s^{-1} (*left to right*), with a channel width of 18.75 km s^{-1}. Each tick mark corresponds to 75 km s^{-1}. The integration time was 4 minutes.

north of the compact H II region G0.07+0.04, as that region was mapped previously by Genzel et al. (1990).

A composite map of the [C II] emission between $v_{\rm LSR} = 0$ and −60 km s^{-1} from the entire Galactic center region including the thermal filaments of the bridge, assembled from the new data and the data from Genzel et al. (1990), is shown in Figure 3 (Plate L3) superposed on the radio continuum map of Yusef-Zadeh et al. (1984).

2.1. *Mass and Luminosity of* [C II] *in the Central 50 Parsecs*

Integrated over the map in Figure 2, the [C II] line luminosity is about 3×10^4 $L_\odot$ within an area of 860 pc^2 or about an order of magnitude greater than in the circumnuclear disk where we find about 2×10^3 $L_\odot$ within 30 pc^2 (cf. also Genzel et al. 1985; Lugten et al. 1986; Okuda et al. 1989). In the "bridge" between the circumnuclear region and the radio arc that is addressed below, we find about 1.2×10^3 $L_\odot$.

A lower bound to the C^+ column densities in the optically thin limit and for infinite temperature and density is obtained directly from the observed [C II] intensities (see Crawford et al. 1985). For the "lobes" of the circumnuclear disk, we get a column density $N(C^+) \geq 1.4 \times 10^{18}$ cm^{-2}, and even in the "bridge" a column density $N(C^+) \geq 8 \times 10^{17}$ cm^{-2} is found. With hydrogen densities in the C^+ regions of a few 10^3 cm^{-3} and gas kinetic temperatures between 200 and 300 K, as inferred from the ratio of the [C II] line flux to the 63 μm [O I] line flux (Erickson et al. 1991), the actual values will be higher by a factor of 2 or 3.

Assuming therefore a (conservative) correction factor of 2 for the C^+ column density and a C^+/H_2 fractional abundance of $\leq 3 \times 10^{-4}$, we derive molecular hydrogen masses in C^+ regions of $\geq 4 \times 10^3$ $M_\odot$ in the circumnuclear region, $\geq 2.5 \times 10^3$ $M_\odot$ in the "bridge," and a total of $\geq 5.5 \times 10^4$ $M_\odot$ in the mapped area. The latter corresponds to about 5% of the molecular mass in the same region (Bally et al. 1987; Serabyn & Güsten 1987; Mezger et al. 1989).

2.2. [C II] *Emission from the Sgr A Complex*

The strongest [C II] emission (peak integrated brightness 2.6×10^{-3} ergs s^{-1} cm^{-2} sr^{-1} in our beam) comes from the circumnuclear ring or disk surrounding Sgr A West (Figs. 1 and 2; cf. Genzel et al. 1985). Our data toward this region are in good agreement with the previous [C II] measurements of Lugten et al. (1986); we will, therefore, give here only a brief discussion. The integrated [C II] emission (lower right in Fig. 2) shows a double-lobed structure peaking about 50" north and south of the center, indicating a distribution similar to that found in a number of molecular lines and the FIR continuum. C^+ ions clearly are mixed in with the molecular material in the ring, suggesting that ultraviolet (UV) radiation from the center penetrates several parsecs into the surrounding clumpy gas cloud (see Genzel et al. 1985). The kinematics of the circumnuclear far-infrared line emission, showing redshifted gas north and blueshifted gas south of Sgr A* (Figs. 1 and 2), is in good agreement with the ≈ 100 km s^{-1} rotation of the ring derived from various data sets (cf. Lugten et al. 1986; Güsten et al. 1987). There is no evidence for enhanced [C II] emission at the location of the nonthermal radio source Sgr A East.

2.3. *The Relationship between Sgr A and the Radio Arc*

The new [C II] data strongly suggest a continuous physical connection between the Sgr A complex and the curved, thermal filaments of the radio arc's bridge about 10' north of it.

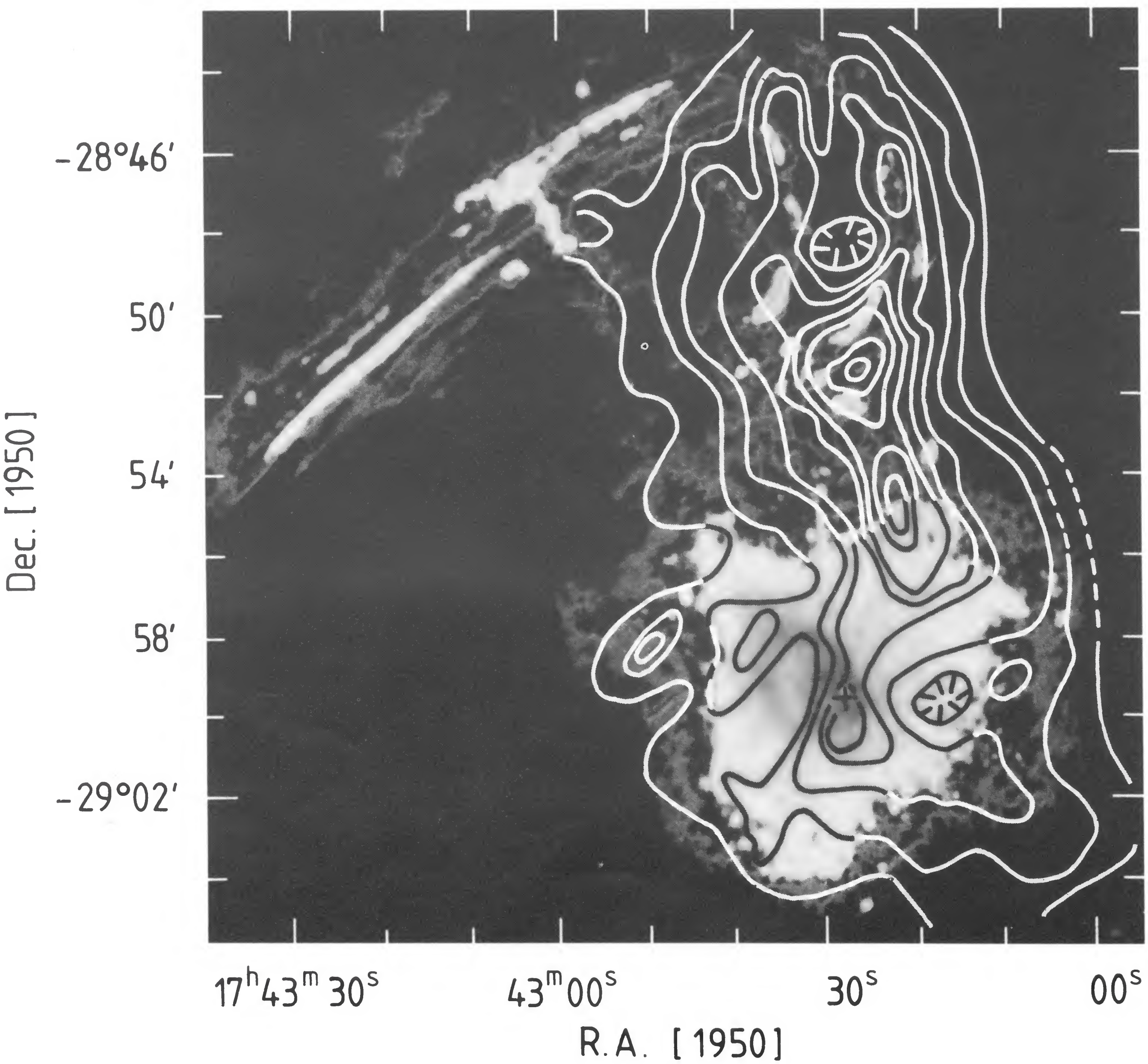

FIG. 3.—Composite map of the [C II] emission between LSR −60 and 0 km s^{-1}, superposed on the 20 cm radio continuum map of Yusef-Zadeh, Morris, & Chance (1984). The far-infrared map was assembled from the present data set up to decl. = −28°52′ and from the data set by Genzel et al. (1990) north of that line. Contour unit is 1.1×10^{-4} ergs s^{-1} cm^{-2} sr^{-1} (9.4×10^{-15} W m^{-2}). The cross marks the position of Sgr A*. The lowest contours are somewhat uncertain due to the finite chopper throw.

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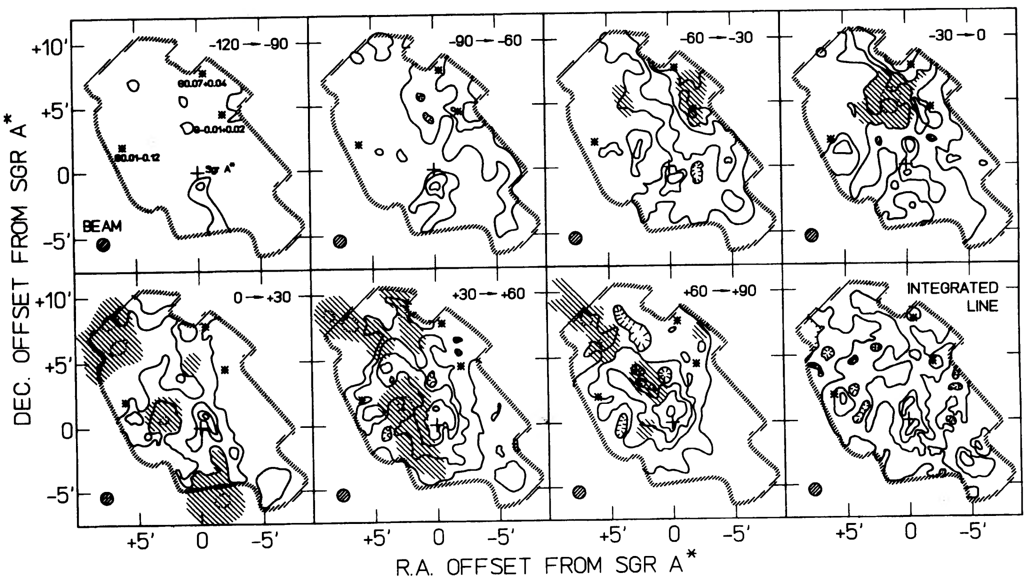

FIG. 2.—Maps of the [C II] ($^2P_{3/2} \rightarrow {}^2P_{1/2}$) emission intensity in the central 50 pc of the Galaxy, for each velocity resolution element (≈ 30 km s^{-1}). A map of integrated [C II] intensity is shown in the bottom right inset. The maps are constructed from 22 different pointings of the array, resulting in 550 spectra. The coverage in the central 5′ is close to fully sampled; the rest is sampled to at least one beamwidth (53″ FWHM). The chopper throw was 7′.5 approximately perpendicular to the Galactic plane (position angle 120° east of north). The reference beam was placed southeast for the measurements at approximately negative Galactic latitude offsets from Sgr A*, and northwest for those at positive offsets. The reference position is Sgr A* (R.A. = $17^h42^m29^s.3$, decl. = $-28°59'19''$ [1950] marked by a cross on all maps. Asterisks mark the positions of three prominent compact H II regions. The [C II] contours are linear with a contour interval of 1.1×10^{-4} ergs s^{-1} cm^{-2} sr^{-1} (9.4×10^{-15} W m^{-2}) for the channel maps, and a contour interval of 4.2×10^{-4} ergs s^{-1} cm^{-2} sr^{-1} (3.6×10^{-14} W m^{-2}) for the integrated intensity map. The peak integrated intensity is 2.1×10^{-3} ergs s^{-1} cm^{-2} sr^{-1}. The hatched regions denote the distribution (50% and 85% contours) of CS $1 \rightarrow 0$ line emission from Tsuboi (1988) with a 32″ beam.

There is a continuous bridge of bright integrated ($\approx 10^{-3}$ ergs s^{-1} cm^{-2} sr^{-1}) [C II] emission leading from the circumnuclear region north to the radio arc, past the compact H II regions G−0.01+0.02 and G0.07+0.04 (Fig. 2). This connection is mostly based on the morphology of the blue shifted gas ($v_{LSR} \approx 0$ to -60 km s^{-1}). [C II] emission in this velocity interval is shown in Figure 3 and clearly indicates a physical link between Sgr A and the radio arc (see also Serabyn & Güsten 1987) supporting the hypothesis that the unique radio arc is in fact located in the inner 50 pc of the Galaxy. The previous uncertainty about the relationship between these sources mainly comes from the lack of bright thermal radio emission between Sgr A* and G0.07+0.04 at the southern end of the arc (cf. Morris & Yusef-Zadeh 1989). The radio interferometric observations trace small-scale, high-contrast emission. Our new measurements suggest that the gap in the radio emission may simply be due to a lack of high-density material or excitation. Assuming that the excitation is due to photoionization, the radio emission requires much harder UV photons which are more easily absorbed than the softer UV photons required for [C II] emission.

2.4. [C II] *Emission and Galactic Center Molecular Clouds*

[C II] emission outside of the circumnuclear region comes preferentially from the edges and surfaces of the large Galactic center molecular clouds. Figure 2 compares the spatial distributions of the [C II] emission with that of the 7 mm CS $1 \rightarrow 0$ emission (from Tsuboi 1988) in different velocity intervals. In most of the velocity channel maps [C II] and mm line emission show a distinct spatial anticorrelation. The brightest [C II] emission appears only on one side of a cloud, or seems to wrap around part of its outer edge. This effect is particularly clear for the +50 km s^{-1} cloud east of Sgr A (Fig. 2, $+30 \rightarrow +60$ panel).

Assuming that the [C II] emission in the Galactic center is tracing photodissociation regions excited by UV radiation, as in many other Galactic and extragalactic sources, we conclude that the massive Galactic center molecular clouds are partially heated by external radiation. This in contrast to many massive clouds within the disk of the Galaxy which contain luminous embedded OB stars. They commonly have [C II] emission peaks centered on or near molecular column density peaks associated with these star forming sites (Stacey et al. 1991b; Stutzki et al. 1988).

In the case of the cloud system with velocities between 0 and +90 km s^{-1} the maps in Figure 2 also indicate that most of the [C II] emission is on the sides facing the Galactic center. This is particularly apparent for the clouds between 20 and 70 km s^{-1} LSR east and adjacent to the circumnuclear ring (the +20 to +50 km s^{-1} cloud systems) which indicates that these clouds may be heated externally by UV photons emerging from the central 5 pc and hence are located in the central 10 pc of the Galaxy (cf. Lugten et al. 1986; Genzel et al. 1990). A similar conclusion is attained through the evidence for dynamic interaction between the +50 km s^{-1} cloud and Sgr A East (Mezger et al. 1989; Ho et al. 1988; Genzel et al. 1990). Based on the above argument, Figure 2 illustrates that the ~20 km s^{-1} molecular gas is farther from the central ionizing source and that the increasingly redshifted gas is closer to the center.

The hypothesis that the Galactic center itself is the heating/ionization source for the blueshifted cloud system leading up to the arc cannot be excluded, but is less likely. The brightest [C II] emission associated with the massive cloud at $v_{LSR} \approx -20$ km s^{-1} $\approx 5'$ north of Sgr A* is not on the side facing the

Galactic center but perpendicular to it. On the other hand, there is a remarkable correlation between the location of the H II regions indicated in Figure 2 and the peaks in the [C II] emission shown in Figure 3. Consequently we propose that the UV photons necessary to account for the [C II] emission north of the Sgr A complex are generated locally, perhaps in OB stars associated with the H II regions G-0.01+0.02 and G0.07+0.04.

2.5. *Mass Accretion into the Circumnuclear Region*

The new [C II] data suggest a close physical connection between the central few parsecs and two massive cloud systems, one redshifted (the +20 to +50 km s^{-1} cloud/streamer proposed to lie in front of the central stellar cluster and the +50 km s^{-1} cloud thought to lie behind), located $\sim 2'$ east of the center, and one blueshifted (0 to -50 km s^{-1}) and located 5′ northwest of the center. They could be feeding gas into the central region containing the circumnuclear ring and the ionized "minispiral." Both can be traced from a distance of 10′ or more to within 1′ of Sgr A*. The kinematics of both systems is not consistent with "normal" Galactic rotation. The +20 to +50 km s^{-1} cloud system appears to be one kinematic feature with the lower velocities located farther from Sgr A* (cf. Güsten & Downes 1980; Güsten et al. 1981; Armstrong & Barrett 1985) and a line-of-sight velocity of about 40 km s^{-1} at 0 longitude offset from the dynamical center, suggesting a radial motion of the same magnitude. This cloud system is also seen to absorb the 2 μm radiation of the central stellar cluster, and hence must be in front of it (Lebofsky 1979; Glass, Catchpole, & Whitelock 1987; Zylka, Mezger, & Wink 1990). Our results support the conclusion of Mezger et al. (1989) that the +20 to +50 km s^{-1} cloud belongs to a coherent cloud system in front of Sgr A that is on a noncircular orbit and falling toward the center. From its mass ($\geq 10^5\ M_\odot$), infall velocity (≈ 40 km s^{-1}), and distance from the center (≈ 10 pc), the current mass infall rate is a few $10^{-1}\ M_\odot$ per year from this streamer alone. Such a large mass accretion rate is sufficient to maintain a dense circumnuclear disk in a turbulent state for a relatively long time ($\gg 10^6$ yr).

The system of blueshifted clouds may be the corresponding feature on the other side of the center. It too must have a substantial noncircular motion (cf. Serabyn & Güsten 1987; Bally et al. 1988). The high column density cloud at -25 km s^{-1} 5′ north of Sgr A* does not appear to correlate with strong extinction of the 2 μm stellar radiation on the maps of Glass et al. (1987) or Gatley et al. (1989). We tentatively conclude then that the blueshifted cloud system is behind the Galactic center and also falling inward to the central region.

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REFERENCES

Armstrong, J. T., & Barrett, A. H. 1985, ApJS, 57, 535
Bally, J., Stark, A. A., Wilson, E. W., & Henkel, C. 1988, ApJ, 324, 223
Crawford, M. K., Genzel, R., Townes, C. H., & Watson, D. M. 1985, ApJ, 291, 755
Erickson, E. F., Colgan, S. W. J., Simpson, J. P., Rubin, R. H., Morris, M., & Haas, M. R. 1991, ApJ, 370, L69
Flaud, J. M., Camy-Peyret, C., & Johns, J. W. C. 1983, Canadian J. Phys., 61, 1462
Gatley, I., Joyce, R., Fowler, A., DePoy, D., & Probst, R. 1989, in The Center of the Galaxy, ed. M. Morris (Dordrecht: Reidel), 361
Geis, N. 1991, Dissertation, Ludwig-Maximilians-University, Munich
Genzel, R., Stacey, G. J., Harris, A. I., Townes, C. H., Geis, N., Graf, U. U., Poglitsch, A., & Stutzki, J. 1990, ApJ, 356, 160
Genzel, R., Watson, D. M., Crawford, M. K., & Townes, C. H. 1985, ApJ, 297, 766
Glass, I. S., Catchpole, R. M., & Whitelock, P. A. 1987, MNRAS, 227, 373
Güsten, R., & Downes, D. 1980, A&A, 87, 6
Güsten, R., Genzel, R., Wright, M. C. H., Jaffe, D. T., Stutzki, J., & Harris, A. I. 1987, ApJ, 318, 124
Güsten, R., Walmsley, C. M., & Pauls, T. A. 1981, A&A, 103, 197
Ho, P. T. P., Jackson, J. M., Armstrong, J. T., & Szczepanski, J. C. 1988, BAAS, 20, 1018
Lebofsky, M. J. 1979, AJ, 84, 324
Lugten, J. B., Genzel, R., Crawford, M. K., & Townes, C. H. 1986, ApJ, 306, 691
Mezger, P. G., Zylka, R., Salter, C. J., Wink, J. E., Chini, R., Kreysa, E., & Tuffs, R. 1989, A&A, 209, 337
Morris, M., & Yusef-Zadeh, F. 1989, ApJ, 343, 703
Okuda, H., et al. 1989, in IAU Symposium 136, The Center of the Galaxy, ed. M. Morris (Dordrecht: Kluwer), 145
Poglitsch, A., et al. 1991, Internat. J. Infrared Millimeter Waves, in press
Reid, M. 1989, in The Center of the Galaxy, ed. M. Morris (Dordrecht: Kluwer), 37
Serabyn, E., & Güsten, R. 1987, A&A, 184, 133
———. 1990, preprint
Stacey, G., et al. 1991a, Internat. J. Infrared Millimeter Waves, submitted
Stacey, G., Geis, N., Genzel, R., Lugten, J. B., Poglitsch, A., Sternberg, A., & Townes, C. H. 1991b, ApJ 373, 423
Stutzki, J., Stacey, G. J., Genzel, R., Harris, A. I., Jaffe, D. T., & Lugten, J. B. 1988, ApJ, 322, 379
Tsuboi, M. 1988, Ph.D. thesis, University of Tokyo
Yusef-Zadeh, F., Morris, M., & Chance, D. 1984, Nature, 310, 557
Zylka, R., Mezger, P. G., & Wink, J. E. 1990, A&A, in press

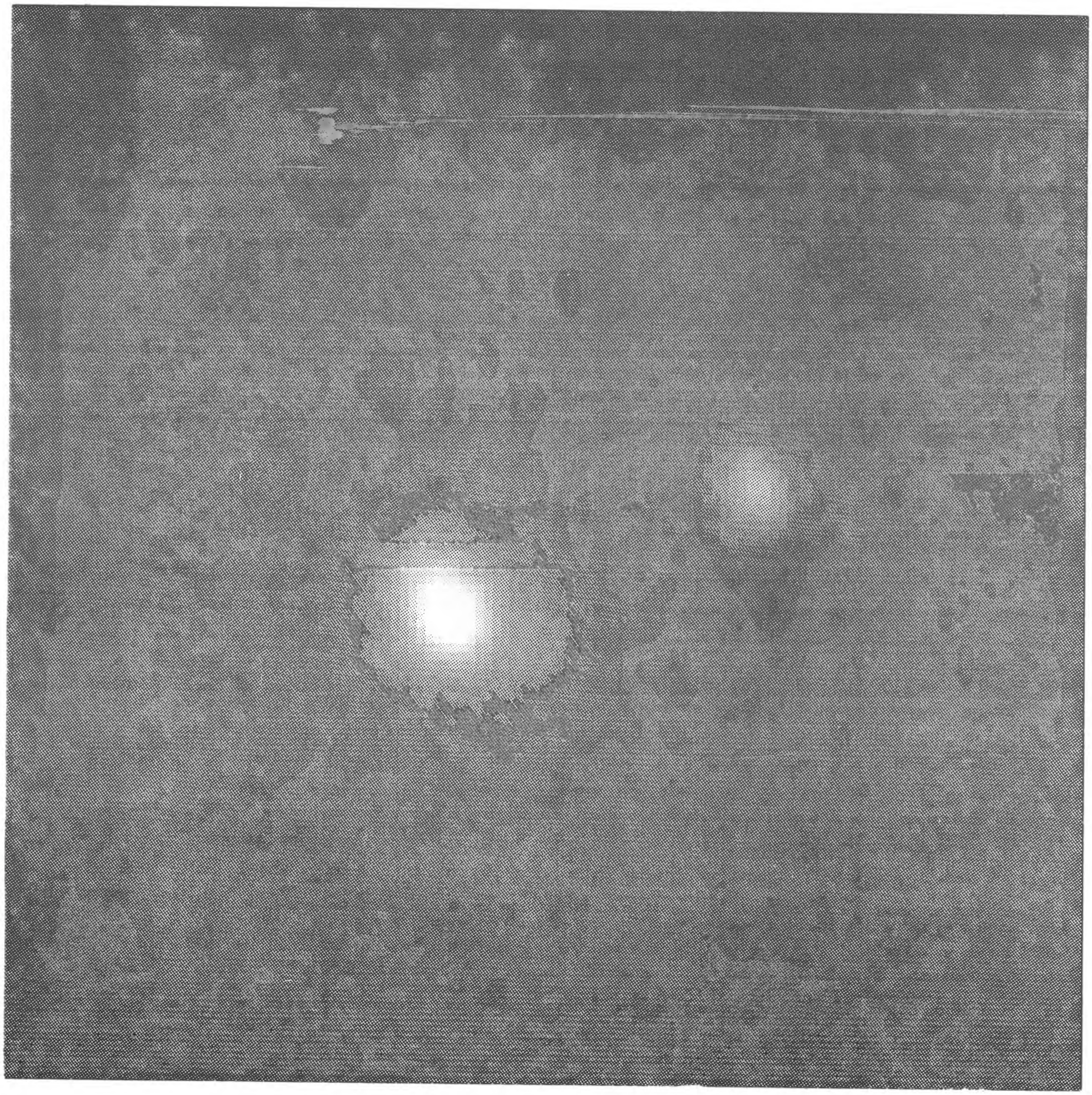

FIG. 1.—Faint Object Camera f/96 image of the Pluto-Charon system. Exposure time was 892 s through filter F342W. Separation between Pluto and Charon in this image is 0\".87; position angle is 172°. Display levels are chosen such that the brightest area roughly corresponds to the planetary disk of Pluto (about 5 pixels in diameter), yet the rings introduced by the *HST* spherical aberration are still visible. Dark feature near Pluto is a reseau mark.

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