A Survey of Radio Recombination Line Emission From The Galactic Center Region

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Abstract. Preliminary results of a systematic survey of H78α, H91α and H98β emission from the inner 40′ of the Galactic center region are presented. This region consists of two prominent continuum features, the Sgr A complex and the radio continuum Arc. In spite of much nonthermal emission arising from these two features, we detected strong line emission with large line widths in more than half of the observed 130 positions. Many of the detections are new, in particular -50 km s^{-1} ionized gas linking the Sgr A complex and the Arc, β line emission from G0.1+0.08 (the arched filaments), and α line emission from the loop-like structures which surround the non-thermal filaments near G0.2−0.05. We find that much of the detected lines are probably associated with the -50 km s^{-1} and the 20 km s^{-1} molecular clouds, known to lie near the Galactic center. We present line profiles of a number of Galactic center sources including Sgr B1, Sgr C and Sgr D.

I. Introduction

The central 40′ of our galaxy consisting of the Sgr A complex and the continuum Arc near $l \sim 0.2°$ is known to exhibit widespread emission of radio recombination lines and linearly polarized emission indicating that both thermal and nonthermal processes operate in this region. Because of the flat spectrum and the large Faraday rotation of the nonthermal features, it is often difficult to identify thermal and nonthermal features. Recently Reich *et al.* (1988) devised a method in which thermal and nonthermal features could be separated by the ratio of far infrared to radio flux densities. On a smaller scale, however, recombination line observations are essential for identifying the thermal components in this complex region.

Previous single-dish surveys of recombination lines from this region (*e.g.,* Pauls *et al.* 1976, Gardner and Whiteoak 1977, Pauls and Mezger 1980) have either sparsely sampled this area or were restricted to sub-regions near the Sgr A complex or the Arc. We present here some preliminary results of a more complete survey of recombination line emission from the inner 40′ of the Galactic center region near λ2cm and λ3.5cm.

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II. λ2cm Observations and Results

The observations were made in November 1987 using the NRAO 43m telescope at Green Bank†. We used the dual polarization upconverter maser receiver located at the Cassegrain focus. The system temperature was typically about 70K, when the antenna was pointed towards an off-source region. The 1024-channel autocorrelator was split into four independent spectrometers, each of 256 channels. The first two spectrometers were connected to one of the polarizations and tuned to the frequency of H78α (13.595 GHz) and H98β (13.558 GHz) recombination lines, respectively. The other two receivers were tuned to the same frequencies and connected to the opposite polarization. We used a bandwidth of 40 MHz on all the spectrometers and centered them at an LSR velocity of 0 km s^{-1}. This resulted in a total velocity coverage of $\pm$850 km s^{-1} and, after hanning smoothing the spectra, a velocity resolution of 6.9 km s^{-1}. The half power beamwidth (FWHM) of the telescope at this frequency is 2 arcminutes. The observations were made in the total power mode. We used the same off-source position (l=0°.35, b = 0°.3) for all the spectra. The on-source and off-source spectra were taken for 6 minutes each. During all the observations, defocusing of the subreflector by $\pm\lambda/8$ from the mean focus position was used to reduce the baseline ripple. Instrumental baselines of up to third order were fitted to regions devoid of line emission, and removed from the spectra, which were obtained in the two polarizations. These two spectra were averaged to obtain the final spectrum for each position.

We observed a total of 129 positions over a grid covering the Sgr A complex, the straight portion of the Arc and the arched filaments. The observed positions, superimposed on a 43 GHz continuum map (Sofue *et al.* 1986), are indicated in Figure 1. The grid points are separated by the FWHM of the beam, *i.e.*, 2′, and therefore, the observed region is undersampled. The λ20cm radiograph, as seen in Figure 2, shows individual substructures whose kinematics are discussed here. The straight portion of the Arc consists of a bundle of nonthermal filaments which run perpendicular to the Galactic plane and cross a series of arched thermal filaments (G0.1+0.08) at positive latitudes (Yusef-Zadeh, Morris and Chance 1984; Yusef-Zadeh, Morris and van Gorkom 1987). A "gap" marks a region separating the arched filaments from the Sgr A complex and an extended loop-like structure centered near G0.2−0.05 constitutes the diffuse emission to the east of the straight filaments (Yusef-Zadeh 1986).

The H76α lines were clearly detected in 64 positions. The positions from which lines are detected can be seen in Figure 3, where we have indicated, on a grid, the Gaussian fitted central velocity (bottom right corner) and the width (top left corner) of the observed lines. Figure 4 shows a sample of profiles obtained in this region. For the region near Sgr A, we were unable to determine accurate profiles because of severe baseline problems caused by the presence of a strong continuum.

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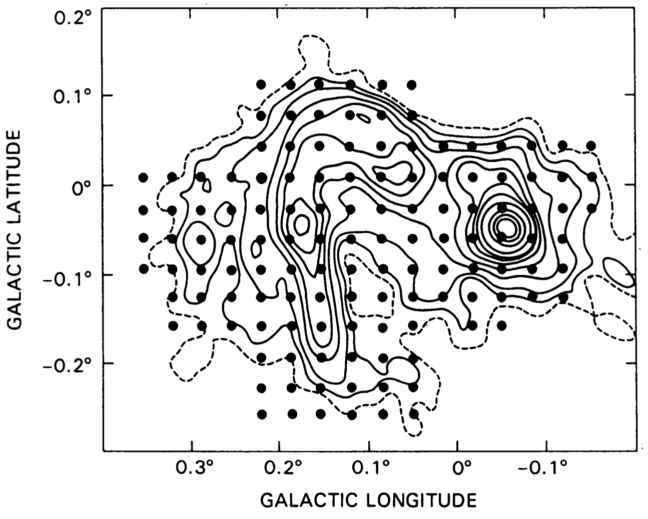

Figure 1: The observed positions separated by 2′ are represented by black dots and are superimposed on the 43GHz map made by Sofue *et al.* 1986.

Figure 2: The λ20cm radiograph of the Arc and the Sgr A complex with a spatial resolution of ~ 30″ × 30″.

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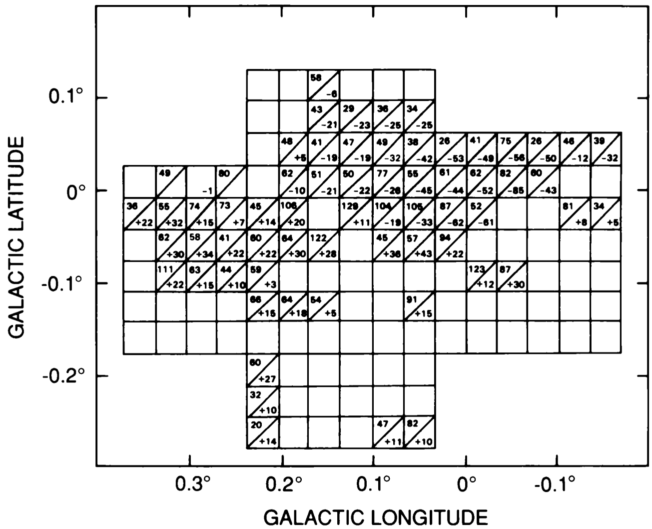

Figure 3: The positions from which H78α line emission have been detected are presented by the Gaussian fitted line widths and central velocities on top left and bottom right corners of each grid point, respectively.

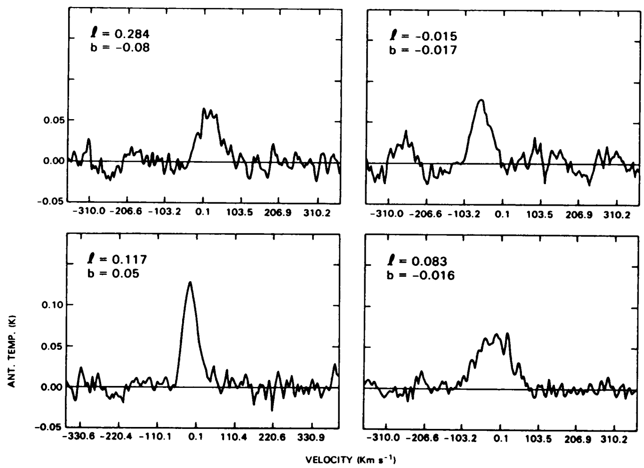

Figure 4: A sample of typical H78α line profiles of the inner 40′ of the Galactic center region with their corresponding Galactic coordinates.

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This region was therefore reobserved at λ3.5cm using a different observing technique as described in the next section.

The kinematics of H76α emission from G0.1+0.08 is consistent with previous single-dish and VLA measurements (Pauls and Mezger 1980; Yusef-Zadeh *et al.* 1987). H98β lines were also detected in seven positions coincident with the arched filaments. The α to β line ratios are in the range 0.30 to 0.40, which is greater than the value, 0.276, expected under conditions of local thermodynamic equilibrium. The negative velocity ionized gas in G0.1+0.08 is spatially and kinematically associated with the -50 km s^{-1} molecular cloud (Serabyn and Güsten 1987). These authors show that the -50 km s^{-1} molecular cloud is concentrated in the "gap" between the Sgr A complex and the arched filaments. A close examination of the velocity structure in Figure 3 indicates that there is indeed much line emission at negative velocities in the "gap" and in the region to the north of the Sgr A complex (see section IV). We note that the negative velocity ionized gas has velocity gradient of $\sim$3 km s^{-1} arcminute^{-1} and typical line widths of $\sim$50 km s $^{-1}$, and the central velocities become more negative as they approach Sgr A. This trend in the velocity distribution is consistent with high-resolution recombination line measurements toward the arched filaments where the ionized gas with the lowest Galactic longitude shows the highest negative velocity (Yusef-Zadeh 1986). Although the continuum features in G0.15+0.08 and in the region near Sgr A (Fig. 2) differ in their morphology, it is very likely that most of the the negative velocity ionized gas arising from the Sgr A complex and the arched filaments are part of a single structure and are associated with the -50 km s^{-1} molecular cloud.

The complex region near G0.2$-$0.05 and extending along the northern half of the Arc is seen to have thermal characteristics and to show emission at velocities which range from 15 to 35 km s^{-1}. Two prominent Galactic center molecular clouds, the 40 km s^{-1} and the 20 km s^{-1}, are known to lie in projection against the continuum Arc (Bally *et al.* 1988). The observed velocity field, although very complex, suggests that the ionized gas may be associated with the 20 km s^{-1} cloud rather than the 40 km s^{-1} one. Based on recent HI absorption study, similar geometry has been proposed by Lasenby *et al.* (1988) who find that the 40 km s^{-1} is located behind the Arc. They argue in favor of an association between the the 20 km s^{-1} molecular cloud and the continuum Arc.

III. λ3.5cm Observations and Results

We used a single polarization upconverter maser receiver at the Cassegrain focus. The off-source system temperature was typically 60K. The receiver was tuned to the frequency of the H91α (8.585 GHz) recombination line. The autocorrelator was used as a single spectrometer of 512 channels. For observations at the peak of Sgr A, a bandwidth of 80 MHz was used. This gave a velocity coverage of $\pm$1395 km s^{-1} and a velocity resolution 10.9 km s^{-1} and enabled us to search for possible broad line emission. For all other positions a bandwidth of 40 MHz was used. Observations were made using the double beam-switching method, which is similar to the method described by Bell and Seaquist (1980). We used a beam throw of

12′. It was ensured that the reference positions did not have any line emission. The baseline ripple was reduced in two stages. First by using the usual $\pm\lambda/8$ defocusing from the nominal focus position, and then by making the same observation after shifting the mean position of the focus by $\lambda/4$. The two spectra were averaged. Instrumental baselines up to fourth order were removed from the final spectrum. In all cases, the widths of the detected lines are much narrower then the bandwidth used.

We observed 6 positions near Sgr A, and at the peaks of Sgr B1, Sgr B2, Sgr C and Sgr D. The 6 positions near Sgr A form a 2×3 grid in α and δ, with a grid separation of 3.5′ which is equal to the FWHM of the beam. Starting from Sgr A centered at $\alpha = 17^h42^m28^s.4$ and $\delta = -28^o59'07''$, the grid extends to the north (N), south (S), west (W), north-west (NW) and south-west (SW). Some of the observed profiles are shown in Fig. 5. The ionized gas to the N, W, and NW of Sgr A appears to correlate kinematically and spatially with the western edge of the -50 km s^{-1} molecular cloud. These positions also coincide with a prominent continuum structure known as the "streamers" which appear to emanate from Sgr A West (Yusef-Zadeh and Morris 1987). The physical association of the negative velocity ionized gas with the "streamers" is consistent with the molecular observations by Serabyn and Güsten (1987) who find an anticorrelation between the molecular materials and the continuum features. They suggest that the -50 km s^{-1} molecular cloud is closely associated with the ionized gas in the arched filaments and in Sgr A.

In Fig. 6, we show the profiles observed towards Sgr A, Sgr B1, SgrC and, SgrD. The parameters of all the observed profiles, obtained from a Gaussian fit, are given in Table 1. The wide line ($\sim$200 km s^{-1}) observed towards Sgr A is consistent with the observations by Pauls *et al.* (1974) at λ6cm and by Mezger and Wink (1986) at λ1.3cm.

IV. Discussion

Much of the line emission detected in the surveyed region arise from the continuum Arc and the Sgr A complex which are known to consist of both thermal and non-thermal gas. G0.15−0.05, which is associated with the Arc, is thought to be the site of an interaction between thermal and nonthermal gas (Yusef-Zadeh *et al.* 1988). Recent far infrared and HI measurements also indicate that the nonthermal shell of Sgr A East is possibly interacting with the 40 km s^{-1} molecular cloud (Mezger *et al.* 1988; Lasenby *et al.* 1988). These characteristics suggest that the HII gas near the Galactic center might, in part, be heated by relativistic particles associated with nonthermal features. This hypothesis could explain the flat spectrum of the nonthermal filaments and the large line widths of ionized gas. The unusual spectrum of the nonthermal gas near the Galactic center could be the result of the depletion of low energy relativistic particles with energies less than 100 Mev, which are known to have large cross sections for ionizing thermal gas (Ginzburg and Syrovatskii 1964). A distinct characteristic of the ionized gas near the Galactic center is the large observed line widths ranging from - 50 to 100 km s^{-1} (Fig. 3). These

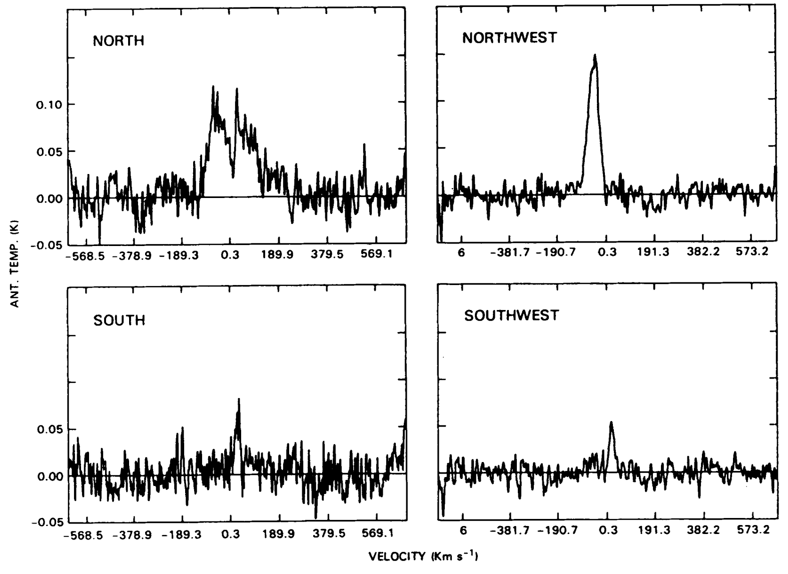

Figure 5: A sample of H91α line profiles of the Sgr A complex. The corresponding positions of these profiles are listed in Table 1.

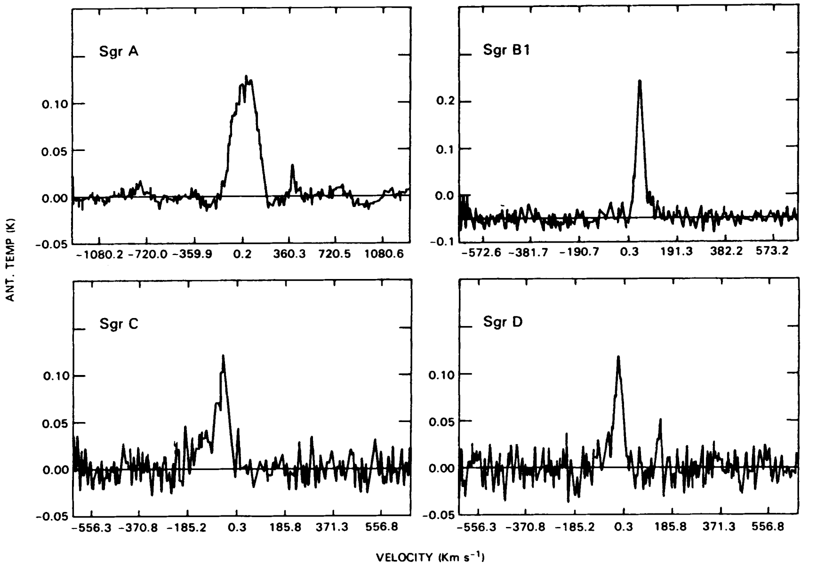

Figure 6: The H91α line profiles of prominent HII complexes near the Galactic center.

Table 1: Parameters of the lines observed at λ3.5cm

Position	α (1950)	δ(1950)	LSR velocity km s^{-1}	Line width km s^{-1}	T_L ^oK
SgrA	$17^h42^m27^s.9$	$-28^o59'03''$	14.7±4.6	192.8±9.1	0.128±0.022
SgrA-N	$17^h42^m28^s.6$	$-28^o55'40''$	−62.3±1.9	52.1±3.8	0.077±0.015
			48.6±3.8	155.9±7.6	0.067±0.015
SgrA-S	$17^h42^m28^s.9$	$-29^o02'44''$	21.8±0.7	28.1±1.3	0.054±0.005
SgrA-W	$17^h32^m13^s.1$	$-28^o59'15''$	−47.6±0.03	139.2±0.1	0.049±0.0001
SgrA-NW	$17^h42^m13^s.0$	$-28^o55'44''$	−50.9±0.7	51.4±1.4	0.136±0.010
SgrA-SW	$17^h42^m13^s.0$	$-29^o02'44''$	17.9±1.3	22.5±2.6	0.050±0.010
SgrB1	$17^h43^m55^s.0$	$-28^o30'56''$	47.2±0.4	36.5±0.8	0.283±0.014
SgrC	$17^h41^m24^s.2$	$-29^o27'13''$	−58.7±1.8	66.0±3.6	0.091±0.015
SgrD	$17^h45^m33^s.2$	$-28^o00'23''$	−20.6±1.2	33.5±2.3	0.101±0.015

are different from the typical widths ($\sim$ 25 km s^{-1}) observed in photoionized HII regions. If the ionization is due to relativistic particles colliding with the thermal gas, then their bulk motion could, in part, be responsible for the large line widths.

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