THE MOLECULAR COMPONENT OF THE GALACTIC CENTER ARCHED FILAMENTS H II COMPLEX: OVRO OBSERVATIONS OF THE CS J = 2–1 LINE

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ABSTRACT

The Owens Valley Radio Observatory (OVRO) millimeter array was used to make observations of the CS (2–1) line (at 97.981 GHz) arising from the G0.07+0.04 region of the “−30 km s⁻¹” molecular cloud near the Galactic center, with a spatial resolution of “~8″. The ionized edge of this cloud forms the Arched Filaments H ii regions, which are ionized by the adjacent Arches stellar cluster. The OVRO data were combined with single-dish data from 1986 obtained at the 30 m IRAM telescope by Serabyn & Güsten. A comparison of these CS (2–1) data and our recent H2co recombination line data reveals that the ionized and molecular gas are physically related, but that their velocities in this region differ by up to 35 km s⁻¹. This difference in velocity can be understood if the gas that gave rise to the G0.07+0.04 H ii region has been fully ionized. An overall comparison of the molecular and ionized gas across the entire −30 km s⁻¹ cloud based on the single-dish CS (2–1) data and the H2co line data illustrates that such differences in velocity between the ionized and molecular gas are common and that the geometric arrangement of these components is complicated. Much of the ionized gas resides on the near side (to the observer) of the molecular cloud; however, in several regions some molecular material must lie in front of the H ii region. The Arches stellar cluster therefore appears to be located in the midst of the molecular cloud, such that some of the near-side cloud surfaces along our line of sight have not been exposed to the ionizing radiation.

Key words: Galaxy: center — ISM: individual (G0.07+0.04) — ISM: kinematics and dynamics — ISM: molecules

On-line material: color figures

1. INTRODUCTION

The interplay between components of the Galactic center’s remarkable “Radio Arc” remains one of the outstanding issues in understanding the interstellar medium in this region. The Radio Arc, which lies ∼30 pc in projection from the center of the Galaxy, Sgr A*, was first revealed in detail with the Very Large Array (VLA) of the National Radio Astronomy Observatory4 over 17 years ago (Yusef-Zadeh, Morris, & Chance 1984). The Arc consists of both thermal and nonthermal structures apparently interacting with each other, but the nature of the physical connections is not well understood. The prominent nonthermal filaments (NTFs) oriented perpendicular to the Galactic plane define the striking linear morphology of the Radio Arc. Eight systems of similar NTFs have been discovered within 250 pc of the Galactic center: typically, they extend for up to 60 pc in length but are very narrow structures (<0.1 pc). The NTFs also show strong linear polarization, have intrinsic magnetic field orientations aligned along their long axis, and have magnetic field strengths estimated at 0.1–1 mG (Tsuboi et al. 1986; Yusef-Zadeh & Morris 1987a; Yusef-Zadeh, Wardle, & Parastaran 1997; Lang et al. 1999a; Lang, Morris, & Echevarria 1999b). The NTFs are thought to trace a large-scale poloidal magnetic field configuration in the inner Galaxy (Morris 1994). However, the origin of the relativistic particles in these synchrotron NTFs and the mechanism for particle acceleration remain unclear.

In addition, two concentrations of ionized and molecular gas appear to be associated with the Radio Arc NTFs: (1) the Sickle (G0.18−0.04), located at the center of the Radio Arc, and (2) the Arched Filaments, which define its western edge (Pauls et al. 1976; Pauls & Mezger 1980; Yusef-Zadeh 1986; Serabyn & Güsten 1987, 1991). VLA observations reveal these sources to be peculiar H ii regions with extremely filamentary morphology, as well as complex velocity structure, although the coherence scale for the thermal filaments is much smaller than that of the NTFs (Yusef-Zadeh & Morris 1987b; Yusef-Zadeh, Morris, & van Gorkom 1987; Lang, Goss, & Wood 1997; Lang, Goss, & Morris 2001, hereafter LGM01). Conventional photoionization was initially dismissed because of the presumed unlikely arrangement of stars required along these H ii structures, and models for heating based on MHD and shock mechanisms were considered (Morris & Yusef-Zadeh 1989; Serabyn & Güsten 1991).

Recently, however, high-resolution infrared observations of this region have significantly advanced our understanding of the thermal radio structures in the Radio Arc. Two extraordinary clusters of young stars (the Quintuplet and Arches clusters) have been discovered, richly populated with O stars and large numbers of Wolf-Rayet and other highly evolved stellar types (Nagata et al. 1995; Figer, McLean, & Morris 1995; Cotera et al. 1996; Serabyn, Shupe, & Figer 1998; Figer et al. 1999a; Figer, McLean, & Morris 1999b). Both radio recombination line and far-infrared observations have shown that the Quintuplet, located at the center of curvature of the Sickle H ii region, can provide adequate ionization of the ionized gas in the Sickle (Lang et

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al. 1997; Simpson et al. 1997). However, ionization of the Arched Filaments has been more difficult to understand in terms of a single cluster, in part because of the large extent and unusual morphology: the Arched Filaments cover $22 \times 16$ pc with an areal filling factor of at most 10%. The uniformity of ionization properties over such a large region, as derived from Kuiper Airborne Observatory far-infrared observations, made the Arched Filaments even more puzzling, as it would be very difficult to distribute stars near the cloud surface in such a way as to account for that uniformity (Colgan et al. 1996).

The recent recombination-line study of LGM01, coupled with the recognition that the Arches stellar cluster generates a substantial ionizing flux ($\sim 2 \times 10^{52}$ photons s$^{-1}$), has revealed that this cluster adequately accounts for the ionization of the thermal Arched Filaments. The uniformity of physical conditions in the ionized gas is likely to be due to the large distance at which the cluster is located from the Arched Filaments (as much as 20 pc along the line of sight). Several outstanding questions remain in understanding this complex, most notably the physical arrangement of the ionized, molecular, and stellar components. Detailed comparisons of the distribution and kinematics of the ionized and molecular gas may offer some insight into the interactions of these components.

Furthermore, the nature of the interaction between the thermal structures and the magnetic filaments is unclear. Serabyn & Güsten (1991) first noted that the molecular material near the Sickle H$\perp$ region may be physically associated with the linear NTFs in the Radio Arc, and that the electrons in the ionized gas may be accelerated to relativistic energies via magnetic reconnection. Follow-up interferometric observations of the CS (2–1) line emission in this cloud by Serabyn & Morris (1994, hereafter SM94) showed that the molecular gas is distributed in discrete clumps corresponding well to positions where both NTFs and ionized gas are present, and where the NTFs undergo striking changes in brightness and continuity. These authors propose that magnetic field reconnection occurs between the cloud field and the field in the magnetic NTFs, thereby causing the acceleration of some of the particles to relativistic energies. The relativistic particles then are constrained to move along the NTFs as they emit synchrotron radiation. This model relies on the presence of three elements: (1) a molecular cloud with a surface moving at a relatively large velocity compared with the intercloud medium; (2) a turbulent, ionized surface on this cloud to provide electrons and sufficient mixing between the cloud and the intercloud medium; and (3) a magnetic field in the partially ionized molecular cloud that has a different orientation than the ambient magnetic field. In fact, far-infrared polarization observations of the gas underlying the Sickle have confirmed that these clouds possess internal magnetic fields aligned along the Galactic plane and therefore perpendicular to the NTFs (Morris & Serabyn 1996). In the region of the Arched Filaments, however, the relationship between the molecular material and the Northern Thread NTF has not been explored, and we thus have an additional site to test the model of SM94.

In order to investigate (1) the arrangement of the ionized, molecular, and stellar components in the Arched Filaments complex and (2) the nature of the intersection of the ionized and molecular gas with the Northern Thread, we carried out high-resolution millimeter observations with the OVRO millimeter array of the molecular gas in a portion of the Arched Filaments known as G0.07+0.04. This portion of the Arched Filaments H$\perp$ complex is intersected by the Northern Thread (Lang et al. 1999b). The three elements required by the model of SM94 (molecular gas, ionized gas, and an NTF) are thus present. Figure 1 shows a diagram of the Arched Filaments with the field of view of the OVRO observations and the prominent sources labeled. In addition, we present a careful comparison of the morphology and velocity structure of the ionized and molecular gas across the Arched Filaments region using the H$2\alpha$ line observations from LGM01 and previously published single-dish molecular line observations from Serabyn & Güsten (1987, hereafter SG87) to provide constraints on the geometric configuration from the components. Details of the OVRO observations, the data reduction, and the combination of the OVRO and 30 m data of SG87 are summarized in § 2; the 3.4 mm continuum and the CS (2–1) line results are presented in § 3, and § 4 provides a discussion of the results. We assume throughout a distance to the Galactic center of 8.0 kpc (Reid 1993).

2. OBSERVATIONS AND DATA REDUCTION

Observations of the W1 Arched Filaments region in the 3.4 mm continuum and CS (2–1) line were made with the six-element array at OVRO in 1998 October, November, and December. Three telescope configurations (equatorial, low, and high) were used, with baselines ranging from 15 to 220 m. Four fields with a primary beam of $\sim 60''$ were observed in a mosaic pattern, with a spacing of 30''. The resulting mosaic covers an area of approximately $2' \times 2'$, centered on the position $\alpha = 17^h 42^m 24.0^s$, $\delta = -28^\circ 49' 40''$ (B1950). In this paper we use B1950 coordinates because the

![Fig. 1.—The 8.3 GHz continuum image of the Arched Filaments H$\perp$ complex (with resolution of $7.8' \times 6.7'$, P.A. $= -1^\circ 0$) from LGM01, showing the different components of the Arched Filaments (E1, E2, W1, W2, G0.10+0.02, and G0.07+0.04), the Radio Arc NTFs and Northern Thread, and the field of view of the OVRO millimeter array observations. In addition, the position of the Arches stellar cluster is indicated by a cross.](image-url)
OVRO data are combined with single-dish data observed in the B1950 reference frame. The total integration time on each field was $\sim$4 hr. NRAO 530, 3C 273, and Neptune were used for gain, passband, and absolute flux calibration, respectively. The data were calibrated using the MMA package (Scoville et al. 1993), and the mosaicking was carried out with the maximum entropy method of deconvolution implemented in the MIRIAD routine MOSMEM (Cornwell & Braun 1988; Sault, Staveley-Smith, & Brouw 1996). The resolution of the final mosaic image is $8''1 \times 4''9$, position angle P.A. = $-10^\circ$8. The CS (2–1) line data were observed at a rest frequency of 97.981 GHz, with 64 channels of 0.5 MHz width, corresponding to a velocity resolution of 1.53 km s$^{-1}$ and a velocity coverage of $\sim$96 km s$^{-1}$. The line was centered on $-40$ km s$^{-1}$. Simultaneous 3.4 mm continuum observations were made with a bandwidth of 1 GHz.

2.1. Addition of Single-Dish Data

The largest spatial scale to which the OVRO interferometer is sensitive is $20''$, corresponding to the shortest baseline of 15 m at 3.4 mm. Therefore, more extended structures are not detected. In order to recover the missing flux density, the total power measurements from single-dish observations of this region have been added. Single-dish observations of the CS (2–1) line in the $-30$ km s$^{-1}$ molecular cloud were carried out with the IRAM 30 m telescope by SG87. Spectra in the vicinity of the Arched Filaments complex were obtained at regular grid spacings of $18''$ and imaged with a single-dish beam size of $\sim25''$. These observations were centered at $V_{\text{LSR}} = 0$ km s$^{-1}$, using a 512-channel filter bank with 1 MHz resolution, which corresponds to a velocity resolution of 3.06 km s$^{-1}$.

Since there is reasonable overlap between the shortest spacings of the OVRO interferometer (4 k\lambda) and the diameter of the 30 m antenna (8 k\lambda), the linear technique of “feathering” single-dish and interferometer data is appropriate. This method requires that the single-dish data be a good representation of the object at low spatial frequencies, and that the interferometer mosaic be a good representation at mid-to-high spatial frequencies. The feathering technique can be carried out using the MIRIAD task IMMERGE. We input deconvolved and restored single-dish and interferometric images with the same velocity resolution and spatial grid. IMMERGE first transforms the images into the Fourier plane, where the data are combined. The single-dish data are given unit weight, and the low spatial frequencies of the interferometer data are downweighted in the Fourier plane with a taper such that a combination of the single-dish and interferometer data results in an image with a Gaussian beam equal in diameter to the beam of the input interferometer mosaic image.

In the case of the 30 m and OVRO millimeter array data, the flux densities in the overlap region (4–8 k\lambda) agree at the 10% level. To prepare the images to match exactly, the interferometer data were smoothed to the velocity resolution of the single-dish observations (1 MHz, or 3.06 km s$^{-1}$) and deconvolved using the MOSMEM algorithm as above, and then convolved with a FWHM = $8''$ taper to give a beam of $8''8 \times 7''8$, P.A. = $-17^\circ$8. A cube was created from the single-dish data with the same number of channels, assuming a Gaussian beam of $25''$, and the units were converted to janskys per beam, using a conversion factor of 4.7 Jy K$^{-1}$ (Mauersberger et al. 1989). The resulting combined image has a resolution the same as the deconvolved interferometer data.

3. RESULTS

3.1. The 3.4 mm Continuum

Figure 2 shows the 3.4 mm continuum emission from the OVRO millimeter array observations overlaid on the 3.6 cm continuum emission from the VLA observations from LGM01. The resolution of the uniformly weighted 3.4 mm continuum image is $9''2 \times 4''6$, P.A. = $-32^\circ$, with an rms noise of 6 mJy beam$^{-1}$. There is close correspondence between the continuum morphology at both frequencies. The 3.4 mm continuum traces the brightest part of the W1 filament (G0.07+0.04), although the 3.4 mm peak (35 mJy beam$^{-1}$) is slightly offset from the 3.6 cm continuum peak. The flux density at 3.4 mm is considerably lower than at 3.6 cm, probably owing to the fact that much of the extended structure at 3.4 mm (>20''$) is resolved out. A visual comparison of the distributions in Figure 2 illustrates that the 3.4 mm observations are only sampling the most compact peak of emission in G0.07+0.04. The 3.4 mm emission does not appear to be dominated by dust emission in the H II region, which would produce a thermal (rising) spectral index. Instead, the 3.6 cm to 3.4 mm spectrum is likely to be flat, consistent with the 3.4 mm detection of the free-free emission from the H II region with a minor contribution from dust emission.

3.2. CS (2–1) Line Emission

Figure 3 shows channel images of the CS (2–1) line from the OVRO observations alone with a resolution of $8''1 \times 4''9$, P.A. = $-10^\circ$8. Most of the emission occurs in the velocity range $-7$ to $-22$ km s$^{-1}$, where the clump of emission appears to be slightly elongated in the east-west direction. Figure 4a shows the CS (2–1) emission from the OVRO data integrated over the velocity range 0 to $-50$ km s$^{-1}$. As in the channel images in Figure 3, the CS (2–1) clump in Figure 4a appears extended in the east-west direction, with a forked structure on the west side. In addition, there is a compact emission structure present to the north of the main emission complex.

Figure 4b shows that the extended CS (2–1) emission has been recovered in the combination of 30 m single-dish and OVRO data. In particular, a diffuse feature is apparent that apparently links the northern component to the southern emission clump. Figure 5 shows spectra from the OVRO-only (Fig. 5a) and 30 m plus OVRO (Fig. 5b) images, integrated over a $\sim1'' \times 1''$ region that includes the CS (2–1) peak. A comparison of these spectra illustrates that we only detect $\sim50\%$ of the total flux density with the OVRO interferometer compared with the resulting combined image. Figure 6 shows the spatial relationship between the ionized gas in the Arched Filaments (shown in 8.3 GHz continuum contours from LGM01) and the CS (2–1) emission (shown in contours and gray scale). The peak of the CS (2–1) emission (at B1950 $\alpha = 17^h42^m26^s50, \delta = -28^\circ50'00")$ is coincident with the 8.3 GHz continuum peak in G0.07+0.04. At the locus of the Northern Thread, the CS (2–1) emission shows a minimum and is bounded on either side by a ridge of emission elongated in a direction along the NTF. The velocity structure of the CS (2–1) emission in this region is
shown in Figure 7. Along four position angles (locations shown in Fig. 7, left), position-velocity diagrams were constructed. In all cases, the velocities decrease to the south. Along cuts B and D, the velocity has a nearly constant value ($v \approx 10$ km s$^{-1}$), whereas along A and C there are velocity gradients up to 5 km s$^{-1}$ pc$^{-1}$.

In order to understand the physical relationship between the molecular and ionized gas, the velocities and line shapes of these components can be compared. CS (2–1) line profiles from these observations and the H$\alpha$ emission from LGM01 were sampled at the same positions near G0.07+0.04 and are overlaid in Figure 8. The most striking feature of the profile comparison is that at all positions across the molecular gas clump, there is an offset between the velocities of the H$\alpha$ and CS (2–1) lines of as much as 35 km s$^{-1}$. The H$\alpha$ emission in this region is characterized by velocities of about $-40$ km s$^{-1}$, whereas the CS (2–1) emission has velocities between $-10$ and $-15$ km s$^{-1}$. Figure 8a represents the peak of the CS (2–1) emission, and there is good correspondence in position between the strong H$\alpha$ and CS (2–1) emission even though the velocities are quite discrepant. In the western region of the clump (Figs. 8c and 8d), the H$\alpha$ lines are weak, but they may be associated with components of the CS (2–1) emission that appear at velocities of $-40$ km s$^{-1}$. In addition, the CS (2–1) spectra appear to have double peaks with velocity components of $-20$ to $-25$ km s$^{-1}$ and $-10$ to $-15$ km s$^{-1}$ in Figures 8d, 8e, and 8f. These double CS (2–1) profiles are consistent with the two velocity components detected in the molecular emission along cut B (see Fig. 7).

4. INTERPRETATION

In this section, we discuss the physical relationships between the components of the Arched Filaments complex:
the $-30\,\text{km}\,\text{s}^{-1}$ molecular cloud, the ionized gas, the Arches stellar cluster, and the Northern Thread. First we consider the implications of the combined OVRO and 30 m CS (2–1) observations of the southern region of the W1 Arched Filament, G0.07+0.04. Second, we examine the relationship between the ionized and molecular gas over the entire region of the Arched Filaments and attempt to elucidate the relative locations of the gaseous features and the Arches stellar cluster.

4.1. Molecular Emission near G0.07+0.04

4.1.1. Relationship between Molecular and Ionized Gas in G0.07+0.04

The morphology and the velocities of the components in this particular region of the Arched Filaments complex show striking differences. Locally, the CS (2–1) emission defines a ridge oriented in the east-west direction (Fig. 6), in contrast to the north-south elongated emission in the ionized W1 filament. Differences in velocity between the ionized and molecular gas are in some cases up to 35 km s$^{-1}$, far exceeding the typical sound speed in an H$\text{ii}$ region ($\sim10\,\text{km}\,\text{s}^{-1}$). These discrepancies raise the question whether the ionized and molecular components in this region are physically related. The velocity differences would suggest that these components are not related. Yet, the presence of some molecular material at velocities of $-40\,\text{km}\,\text{s}^{-1}$ in this cloud complex (see SG87 and below in § 4.2.2) indicates that in the vicinity of G0.07+0.04, molecular material at $-40\,\text{km}\,\text{s}^{-1}$ may have been almost fully ionized, leaving only the filamentary H$\text{ii}$ remnant G0.07+0.04. In other portions of the cloud complex, where complete ionization has not yet occurred, the velocities and morphologies of the components appear to be more closely correlated than in the G0.07+0.04 region (see § 4.2). In addition, the peaks in the CS (2–1) and H92$\alpha$ lines occur at the same location (see Fig. 6) despite the dramatically different morphologies in this particular region. Overall, the highly unusual negative values of velocity characterizing both the ionized and molecular gas in this Galactic quadrant and the larger scale similarities in morphology indicate that these components are likely to be physically related.

4.1.2. Association between the Molecular Gas and Northern Thread

A comparison of the 8.3 GHz radio continuum with the distribution of CS (2–1) emission (Fig. 6) reveals that there is a concentration of molecular gas surrounding the intersection of the NTF with the ionized W1 Arched Filament. The distribution of molecular emission in Figure 6 resembles the clumps of CS (2–1) emission that SM94 observed at several positions in the molecular cloud associated with the NTFs of the Radio Arc and the Sickle H$\text{ii}$ region. Therefore, we are detecting the close positional relationship between the NTF, the ionized gas, and the molecular gas that SM94 rely on for their particle acceleration mechanism. In Figure 6, the Northern Thread is essentially tangent to the clump displaying the strongest CS (2–1) peak, and the CS (2–1) emission is concentrated into two parallel ridges of extent $\sim1'$ (2.5 pc) on both sides of this NTF. However, this only represents one of the many positions in this cloud complex where the NTFs appear to intersect, and it is difficult to demonstrate that these components are physically interacting. In addition, the existing high-resolution data cover only a small fraction of the total area of the $-30\,\text{km}\,\text{s}^{-1}$ cloud. In order to determine whether the molecular clump–NTF relationship is present exclusively at positions where NTFs intersect the molecular gas in the Arched Filaments complex (as in SM94), further high-resolution molecular observations of the entire cloud would be required.
4.2. Relationship between Molecular and Ionized Gas throughout the Arched Filaments Complex

Several previous studies have established that the ionized and molecular gas in the Arched Filaments complex are closely associated (Güsten & Downes 1980; Yusef-Zadeh 1986; Bally et al. 1987; SG87). Of these studies, SG87 present a comparison of the molecular emission [CS (2–1)] lines and the ionized gas (from the H110α data of Yusef-Zadeh 1986). The H110α data have a spatial resolution of 22″ and do not cover the full extent of the ionized structures, but they confirm that the velocities of the gas components correspond well. Here, however, we provide a more complete examination of the morphology and kinematics of these gaseous components by comparing the data of SG87 with the recent H92α line data from LGM01 (spatial resolution of ~13″), which cover the entire field of view of the Arched Filaments with adequate signal-to-noise ratio.

Fig. 4.—The CS (2–1) emission integrated over the range 0 to −55 km s⁻¹ from (a) OVRO-only observations with a resolution of 8.1 × 4.9, P.A. = −10°, and (b) OVRO + 30 m data that have a resolution of 8.8 × 7.8, P.A. = −17°. In (a), the gray-scale and contour levels represent −0.06, 0.06, 0.1, 0.18, 0.22, 0.26, 0.30, 0.34, 0.38, and 0.42 Jy beam⁻¹ km s⁻¹; in (b), the gray-scale and contours represent levels of 4, 8, 12, 16, 20, 24, 28, 32, and Jy beam⁻¹ km s⁻¹.
The missing flux density in the interferometer data is apparent in comparison with the OVRO + 30 m spectrum. The spatial coincidence of the edges of the CS (2–1) and H92α emission regions is striking. SG87 first pointed out this correspondence (see Fig. 5 of SG87), but here Figures 9a–9c more clearly demonstrate this point. At several locations, the ionized gas lies exactly at the edge of the molecular gas. For example, in Figure 9c the strongest peaks of the H92α line emission (gray scale) along the E2 filament occur just at the edge of the molecular gas (light contours), at \((17^h42^m36^s0, -28^\circ49'15''\) and \((17^h42^m36^s0, -28^\circ46'00''\). The morphology of the molecular gas also corresponds well to the curvature of the E2 ionized filament at these locations. In Figure 9b, the southern boundary of the ionized portion of the western filaments seems to coincide exactly with the northern boundary of molecular gas in this velocity range.

In both Figures 9b and 9c, the prominent H ii complex G0.10+0.12 has no direct molecular counterpart, but it is surrounded on either side spatially by molecular material; this anticorrelation suggests that this one portion of an otherwise continuous molecular cloud has been completely ionized. At other locations, the distributions of ionized and molecular gas correspond very closely, most notably in Figure 9c. SG87 suggest that the coincidence of the molecular gas along edges of ionized gas indicates that the cloud is being ionized from the side, whereas the close spatial correspondence of molecular and ionized features indicates that the ionization occurs on a cloud side facing the line of sight.

4.2.2. Velocity Structure

Beyond the correspondence in overall morphology, the ionized and molecular features also agree well in their central line velocities. The squares in Figure 10 (center) represent positions at which the central velocity and line shape of the CS (2–1) and H92α lines are compared. A sample of these profiles is shown in Figures 10a–10j. The majority of the profiles shown in Figure 10 (all except Figs. 10g and 10i) show that the differences between velocities of at least one component of ionized and molecular gas are less than 20 km s\(^{-1}\). For visual reference, the differences in velocities between the H92α and CS (2–1) components at each position are indicated as either blueshifted (black squares) or redshifted (white squares) with respect to the H92α line central velocity.

Double-peaked CS (2–1) profiles are observed in several locations throughout this complex, and they appear to be similar to the double-peaked structure in the H92α line profiles of LGM01. In the northern portion of the western filaments where W1 and W2 intersect (\((\alpha = 17^h42^m22^s0, \delta = -28^\circ46'30''\) and \((\alpha = -28^\circ48'00''\), the H92α profiles have a double-peaked structure (see Fig. 10c), which is attributed to the superposition of spatially adjacent components of ionized gas that have different velocities. The same interpretation might be applied to the two components of molecular gas at \(-40\) and \(-10\) km s\(^{-1}\) (Fig. 10d), as this region is coincident with the intersection of these two filaments (W1 and W2).

A further examination of the velocity structure of the ionized and molecular components was made by comparing the position-velocity structure of the ionized and molecular

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**Fig. 5.** The CS (2–1) spectra integrated over a 1’ × 1’ region surrounding the peak emission from (a) the OVRO-only data and (b) the OVRO + 30 m data. The missing flux density in the interferometer data is apparent in comparison with the OVRO + 30 m spectrum.
gas. Figure 11 shows a finding chart for the position-velocity diagrams shown in Figures 12a–12d. The labels ABCD in Figure 11 correspond to Figures 12a (E1), 12b (E2), 12c (W1), and 12d (W2), respectively. In addition, three reference markers (1, 2, 3) are indicated in Figure 11 along each filament, corresponding to positions along each of the filaments in Figures 12a–12d.

Overall, these figures suggest that some anticorrelations exist on small scales in the velocities of the ionized and molecular emission, further supporting the idea that the morphology and arrangement of ionized and molecular gas are unusually complex. For example, at position 2 in Figure 12a, the molecular gas is clearly double peaked ($v \sim -17$ and $-37$ km s$^{-1}$), whereas the spatially coincident ionized gas has a velocity of $v \sim -25$ km s$^{-1}$, as if located between the two molecular features in velocity. Also, between positions 1 and 2 in Figure 12b the velocity of the ionized gas ($v \sim -20$ km s$^{-1}$) corresponds roughly to one of the peaks of molecular emission, yet there is a second component of molecular emission with a more negative velocity (about $-40$ km s$^{-1}$) and a clear lack of ionized gas in this velocity range. A comparison of the position-velocity diagrams for the ionized and molecular gas in G0.10–0.02 confirms that this strong H II complex likely represents the ionized portion of an otherwise continuous molecular cloud. The peak of molecular gas in the E2 filament occurs around position 1 (2' along its length) in Figure 12b. Further along the E2 filament, near position 3, the molecular emission is much weaker, and the ionized gas has a peak around $-20$ km s$^{-1}$, suggesting that the molecular material in that velocity range has been mostly ionized; as Figures 9b and 9c show, the molecular material may have a continuous distribution on either side of the ionized component.

![Image of position-velocity diagrams showing anticorrelations between ionized and molecular gas](https://example.com/position-velocity-diagram.png)

**Fig. 6.**—The CS (2–1) emission from the OVRO + 30 m data, integrated over the range 0 to $-50$ km s$^{-1}$, shown with contours and gray scale as in Fig. 4b. The thicker contour overlay represents the VLA 8.3 GHz emission arising from the W1 and W2 Arched Filaments at levels of 24, 36, 48, 72, and 84 mJy beam$^{-1}$, with a resolution of $\sim 8''$ from LGM01. The diagonal line represents the position of the Northern Thread.
4.3. Relative Placement of Components in the Arched Filaments Complex

The majority of H ii regions are located at the edges of molecular clouds, and therefore the velocity structure and morphology of the ionized gas are often closely related to the underlying molecular material (Israel 1978). The distribution of ionized and molecular gas in the Arched Filaments complex may well be related to the “champagne phase” in the evolution of an H ii region (Tenorio-Tagle 1979). This occurs when molecular material in physical contact with the H ii region is evaporated by the ionization by nearby OB stars. In this paradigm, an H ii region is assumed to have formed around a cluster of stars located at the edge of a molecular cloud. The ionization front then breaks out of the molecular gas and begins to expand into the less dense, surrounding interstellar medium, creating a stream of ionized gas that flows off of the molecular cloud’s surface. The result is that one side of the H ii region becomes density bounded, while the other side is ionization bounded.

The simple picture proposed by LGM01 for the arrangement of the cluster and gaseous features is based on the above idea: the Arches cluster lies near the edge of a dense molecular cloud, whose surface is thereby ionized, resulting in a flow of plasma away from the cloud’s surface. For simplicity, the cluster was assumed to be on the near side (closest to the observer along the line of sight) of the cloud in LGM01. Therefore, the “front” side of the molecular cloud would be ionized. In fact, the Brγ (2.166 μm) emission-line study by Cotera et al. (2000) indicates that the ionized gas indeed lies on the near side of the molecular cloud. They observe Brγ emission arising from one of the brightest regions of the Arched Filaments (G0.10+0.12) and conclude, based on a comparison of the theoretical and measured extinction, that the ionized gas in this region cannot be embedded within the molecular cloud and must lie on the side of the feature closest to the observer.

In this picture, if the ionized gas is expanding from the near side of the cloud toward the observer, then the velocities of the H92α line emission might be consistently blueshifted from the molecular line emission. However, Figure 10 shows that the ionized and molecular components do not follow this simple prescription. Although there are regions of the Arches Filaments where the H92α lines appear to be blueshifted relative to the CS (2–1) emission (e.g., the profiles for portions of E1, E2, and much of W1; Figs. 10a, 10b, and 10g), there are also regions where the H92α lines are redshifted relative to the CS (2–1) emission (profiles along W2; Figs. 10d and 10e). The inconsistency of the trend among the velocity
profiles across the Arched Filaments suggests that the cloud may comprise quasi-independent gas features with different velocities and probably different line-of-sight distances, all of which are largely superposed in the plane of the sky to give the impression of a more unified structure. In addition, some portions of the Arched Filaments may be completely ionized and have no immediate molecular counterpart at a similar velocity (as in § 4.1.1); yet, at adjacent positions there is often evidence of molecular gas at similar velocities to the ionized gas, suggesting that the distribution of molecular gas is complex and that ionization has not reached all surfaces equally.

Fig. 8.—Comparison of the velocities and line shapes of the ionized and molecular gas in the G0.07+0.04 region. The gray-scale and contour image represents an overlay of the integrated CS (2–1) emission from the OVRO + 30 m observations and the VLA 8.3 GHz image as shown in Fig. 6. The solid lines in (a)–(f) represent the line profiles of CS (2–1) emission, and the dashed profiles represent the H92α line sampled at the same position (from the data of LGM01). The H92α lines have been scaled by the arbitrary factor shown in the upper left of the panels to fit onto the CS (2–1) scaling.
Previous lower resolution (≈50") VLA observations of H i absorption toward the Radio Arc can provide some geometric constraints. The large H i absorption opacities toward the peaks of radio continuum emission in the westernmost Arched Filaments indicate that a layer of atomic gas lies in front of the ionized gas in W1 and W2 (Lasenby, Lasenby, & Yusef-Zadeh 1989). Lasenby et al. (1989) also find that the H i absorption opacities are reduced toward the eastern filaments, suggesting that at least some ionized material lies on the near side of E1 and E2, and that much of the molecular gas is located behind the ionized gas.

Thus, a more complex geometric arrangement of the components than proposed in LGM01 is warranted. Such an arrangement must account for the unusual morphology...
of the ionized gas, the multiple-peaked structure of both the CS (2–1) and the H92α line profiles in various regions of the Arched Filaments, and the H i absorption results described above. If the stellar cluster resides on the near side of the molecular cloud, as originally proposed in LGM01, one would expect the entire front surface of the molecular cloud to be ionized. The presence of both H i and molecular gas on the near side of the cloud (as described above) is not consistent with this picture. Instead, the narrowness of the Arched Filaments and the presence of molecular gas and H i absorption on the near side of the cloud suggest that the molecular material has a finger-like distribution, of which
only the protruding, narrow edges are ionized. The cluster is likely to be embedded within the distribution of molecular gas such that some of the cloud surfaces along our line of sight have not been exposed to the ionizing radiation.

Figure 13 shows a schematic of such an arrangement of the molecular, ionized, atomic, and stellar components that satisfies some of the observed constraints. The dashed lines in Figure 13 represent positions in the Arched Filaments where multiple-peaked profiles can be explained by a superposition of features along the line of sight. These correspond to four of the profiles in Figure 10: sight lines 1 (Fig. 10f), 2 (Fig. 10h), 3 (Fig. 10g), and 4 (Fig. 10d). In the western filaments, it is apparent that some of the molecular and atomic gas has not been directly exposed to the ionizing radiation of the Arches cluster (most apparent on the western side of the W1 and W2 filaments, where the enhanced H I absorption opacity is present). In the eastern filaments, most of the surfaces of the molecular cloud that are detected have been ionized; therefore, the H I absorption opacity toward this

![Diagram of Arched Filaments](image-url)
region is more reduced than toward the western side. A higher resolution (~15") VLA study of the H I absorption in and around the Arched Filaments complex is currently being carried out and will provide a more reliable picture of the line-of-sight location of these components.

5. CONCLUSIONS

Detections of the 3.4 mm continuum and the CS (2–1) line arising from a region of the −30 km s⁻¹ molecular cloud at the Galactic center were made using the Owens Valley
millimeter array. These data were combined with the corresponding total power data obtained at the 30 m IRAM telescope by Serabyn & Güsten (1987). The following conclusions are made:

1. Continuum emission at 3.4 mm was detected in the G0.07+0.04 region, coincident with the peak of 3.6 cm continuum emission. The spectrum between 3.4 mm and 3.6 cm appears to be flat, consistent with a detection at 3.4 mm of the free-free emission arising from the HI region and with a slight contribution from dust.

2. The combined OVRO and 30 m integrated CS (2–1) emission image shows that, overall, the molecular gas in the G0.07+0.04 region is distributed in a compact clump at the intersection of the ionized filament and Northern Thread. We have therefore detected the type of close positional relationship between ionized gas, molecular gas, and NTF that model for NTF generation of SM94 requires. However, further, more detailed observations will be necessary to verify that this relationship is detected throughout the complex.

3. A comparison between the combined OVRO and 30 m CS observations and the H2O data from Lang et al. (2001) in the region of G0.07+0.04 shows that the molecular and ionized gas are physically related, although the velocities are separated in some places by up to 35 km s⁻¹, indicating that one component of the molecular gas in this direction may have been fully ionized.

4. A larger scale comparison between the 30 m CS observations and the H2O data from Lang et al. (2001) also indicates that the molecular and ionized gas are closely associated across the entire region of the Arched Filaments, as was first discussed by Serabyn & Güsten (1987). The velocities, velocity gradients, and morphology suggest that the ionized gas is physically related to this molecular cloud.

5. The geometric arrangement of the stellar and gaseous components in the Arched Filaments region is complex. Over much of the eastern Arched Filaments (E1 and E2), the ionized gas appears to lie on the near edge of the molecular gas, yet in the western filaments (W2 in particular), some molecular material must lie in front of the ionized gas, consistent with HI absorption results (Lasenby et al. 1989). The narrow and curved morphology of the Arched Filaments therefore suggests that the molecular cloud has a finger-like distribution of molecular material, the edges of which are ionized. The cluster is likely to be embedded within the distribution of molecular gas such that some of the cloud surfaces along our line of sight have not been exposed to the ionizing radiation.

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Fig. 13.—Schematic diagram showing a view of the ionized, molecular, atomic, and stellar components in the Arched Filaments complex from a position “above” the molecular cloud, looking down its long axis. The dashed lines represent certain sight lines through the complex where complicated, double profiles are observed in the molecular and ionized gas. The numbering scheme (1–4) corresponds to sight lines of the CS (2–1) and H2O profiles in Figs. 10j, 10k, 10y, and 10d.
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