We present Spitzer IRS R ∼ 600 spectra (10 – 38 µm) of 38 positions in the Galactic Center (GC), all at the same Galactic longitude of and including the Arches Cluster. Our positions include the Arched Filaments, regions near the Quintuplet Cluster, the “Bubble” lying along the same line-of-sight as the molecular cloud M0.13-0.13, and the diffuse interstellar gas along the line of sight at higher Galactic latitudes. From measurements of the [O IV], [Ne II], [Ne III], [Si II], [S III], [Fe II], [Fe III], and H2 S(0), S(1), and S(2) lines we determine the gas excitation and ionic abundance ratios. The main source of excitation is photoionization, with the Arches Cluster ionizing the Arched Filaments and the Quintuplet Cluster ionizing the gas nearby and at lower Galactic latitudes including the far side of the Bubble. In addition, strong shocks ionize gas to O+3 and destroy dust grains, releasing iron into the interstellar medium (ISM); the shock effects are particularly noticeable in the center of the Bubble but the highly ionized gas is present in all positions. The H2 lines are formed both in photodissociation regions in the GC and along the line of sight to the GC.
Figure 1. Thermal and non-thermal continuum imaged at 21 cm with 11″ resolution by [17]. The observed positions are indicated by square boxes and other locations of interest are labeled.

In this paper we present Spitzer Space Telescope observations of mid-infrared (MIR) spectra of 38 positions in the GC. Our goals are to clarify the source(s) of excitation of the Arched Filaments and to determine the relationship of the Bubble with the clusters and other filaments.

2. Observations
We observed the Galactic Center region with Spitzer’s Infrared Spectrograph [6] with the Short-High and Long-High modules (10 – 38 μm) on 21–23 March 2005. The observed line of positions is shown in Figure 1. The emission from the 2–3 positions at each end of the line probably originate in the diffuse interstellar medium (ISM) all along the line-of-sight to the GC as well as in the GC itself. The data were reduced and calibrated with the S13 pipeline. The basic calibrated data (bcd images) were median-combined and cleaned of rogue pixels and noisy order edges. The spectra were extracted using the Spectroscopic Modeling, Analysis and Reduction Tool [5]. Line and continuum fluxes of the brighter lines were measured by fitting Gaussians plus a sloped continuum to each of the line profiles. Fluxes for the faintest lines were estimated by integrating over the line profile. The extinction correction was estimated by fitting a template of the MIR spectrum of the Orion Nebula [16] to the 10–15 μm spectral region (Simpson et al., in preparation).
3. Results

The fluxes of the ionized lines correlate well with the Arches and Bubble structures seen in the radio (e.g., Fig. 1) and MIR continua, from which we conclude that these lines do indeed originate in the GC. However, the H$_2$ line fluxes peak near the Galactic plane (latitude $\sim -0.05\degree$), similar to the distribution seen in warm CO J=4–3 [11]. The radial velocities of the H$_2$ lines also show a distinctly different pattern from those of the ionized lines. The ratios of the three H$_2$ lines, S(0), S(1), and S(2), show little scatter and indicate that they originate in photo-dissociation regions (PDRs) with densities $\sim 10^4 - 10^5$ and $G_0 < 1000$ cm$^{-3}$, about what we would expect for a GC dense molecular cloud lying at some distance from the exciting stars [7]. There are probably additional contributions to the H$_2$ lines from the PDRs along the line of sight to the GC.

Electron densities ($N_e$) were estimated from the ratios of the density-sensitive [S III] 18.7 and 33.5 $\mu$m lines. These densities are plotted in Figure 2. This ratio is also sensitive to extinction and at some positions the 18.7/33.5 $\mu$m line ratio is below that produced by even the lowest possible $N_e$; for these positions the extinction was increased until the [S III] 18.7/33.5 $\mu$m line ratio corresponded to a minimum $N_e \sim 10$ cm$^{-3}$. Since both [S III] lines are very strong, the chief uncertainty is due to uncertainties in the extinction correction. Using these densities and a typical electron temperature of 6000 K for the GC [8], we computed the excitation and abundance ratios plotted in Figures 3–5.

The H II region excitation can be estimated from the ratio of a doubly ionized line with respect to a singly ionized line of the same element if the ionization potentials of both lines are greater than that of hydrogen (13.6 eV). For Spitzer, the best line pair is the [Ne III] 15.6 $\mu$m
and [Ne II] 12.8 µm lines, since both lines have similar extinction. Figure 3 shows that the highest excitation occurs in the interior of the Bubble region, which may be influenced by the hot stars of the Quintuplet Cluster, and in the diffuse ISM at the ends of the line of positions. Even so, this gas is all “low excitation”, since Ne$^{++}$/Ne$^+ << 1$. The gas ionized by the Arches Cluster is of lower excitation yet, in spite of the fact that the Arches Cluster is supposedly younger than the Quintuplet Cluster [4]. This difference in excitation was already known from our work on the GC H II regions with the Kuiper Airborne Observatory [3, 1, 15] and ISO [2]. We conclude that the Arched Filaments are ionized by the Arches Cluster since the excitation decreases rapidly as one looks at positions at higher Galactic latitudes from the Cluster. This pattern also holds for the S$^{++}$/S$^{+3}$ ratio and the ionization-parameter-sensitive ratio Si$^+/S^{++}$ (Simpson et al. in preparation). Because the gas at the position of the Arches Cluster itself has lower excitation than the two positions at immediately higher Galactic latitudes, we believe that the Arches Cluster lies some distance away from the gas emitting the observed lines and is not directly in contact.

Figure 4 shows the O$^{+3}$/Ne$^+$ ratio (O/Ne $\sim 4$ in Galactic H II regions and is expected to be approximately constant). We see that O$^{+3}$ is most abundant in the center of the Bubble and in the diffuse ISM at the ends of the line of positions. Triply ionized oxygen is not produced in H II regions, except in circumstances of extremely low metallicity (all extragalactic) where there are exceptionally hot stars that emit photons with energies $> 54$ eV. However, [O IV] is seen in some galactic nuclei (normally not low metallicity) and is thought to be produced by high velocity shocks (e.g., [10]). In some low metallicity galactic nuclei, the
[O IV] could be excited by hot Wolf-Rayet stars [14]; however, there is no indication that the O+3 observed here is produced by any of the WR stars in the Arches Cluster. Most likely, the pervasive O+3 seen in the GC is produced by shocks.

For the most part, iron is strongly depleted in the ISM. Figure 5 shows the \((\text{Fe}^+ + \text{Fe}^{++})/(\text{Ne}^+ + \text{Ne}^{++})\) ratio (Solar Fe/Ne \(\sim 0.15 - 0.5\)). We see that gas-phase iron is much more abundant in the Bubble than in the Arched Filaments. A likely explanation is that grains in the Bubble region and diffuse ISM have been destroyed by strong shocks, thereby liberating the iron.

4. Conclusions

(i) The highest excitation, as seen by the excitation indicators Ne++/Ne+, Si+/S++, and O+3/(Ne+ + Ne++), is found in the center of the Bubble and not at the locations of the Arches and Quintuplet Clusters in the plane of the sky. At the present time there is probably a large line-of-sight offset between the clusters and the ionized gas. This is not unreasonable since the clusters, with ages of 2 and 4 My, probably did not form in the same molecular clouds that they are now ionizing.

(ii) The low Galactic latitude rim of the Bubble is ionized by a source at higher Galactic latitude, probably the Quintuplet Cluster. It is not the outer edge of the M0.13-0.13 molecular cloud, which lies along the same line-of-sight as the Bubble.

(iii) The Arched Filaments are ionized by the Arches Cluster.

(iv) There are multiple indicators of strong shocks, peaking in the center of the Bubble. This possibly indicates the location of a violent outflow a few thousand to \(10^4\) years ago.

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