THE IMPACT OF THE GALACTIC CENTER ARCHES CLUSTER: XRAYDIO OBSERVATIONS

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Abstract

The combination of radio, near-infrared and X-ray data over the last few years has revealed that the Galactic center Arches cluster is one of the most extraordinary clusters in the Galaxy, and has a large influence on the surrounding interstellar medium. Several similar clusters inhabit the central 50 pc of the Galaxy and are thought to be responsible for the large-scale radio and diffuse X-ray emission in this region. Such massive and luminous young clusters can serve as analogs to the "super star clusters", that are found in nearby starburst galaxies.

1 Introduction

The Galactic center (GC) Radio Arc (∼ 30 pc in projection from the dynamical center of the Galaxy, Sgr A*) is comprised of unique thermal and nonthermal filaments (Yusef-Zadeh et al. 1984). The nonthermal filaments are known to be magnetic in nature and to trace out prominent magnetic field structures in this region of the Galaxy (Yusef-Zadeh & Morris 1987). The original mechanisms for ionization of the thermal filaments relied on interactions between molecular clouds and these magnetic fields (Morris & Yusef-Zadeh 1989). The advent of high-resolution near-IR instrumentation revealed that two extraordinary, young massive clusters of stars also inhabit the Radio Arc region - the Quintuplet cluster and the Arches cluster (Nagata et al. 1995; Cotera et al. 1996; Figer et al. 1999, 2002). These clusters are thought to contain ∼ 100 O and B type stars, including a large number of highly evolved Wolf-Rayet (WR) stellar types. Such massive clusters strongly impact into the surrounding interstellar mater through ionizing flux and powerful stellar winds.

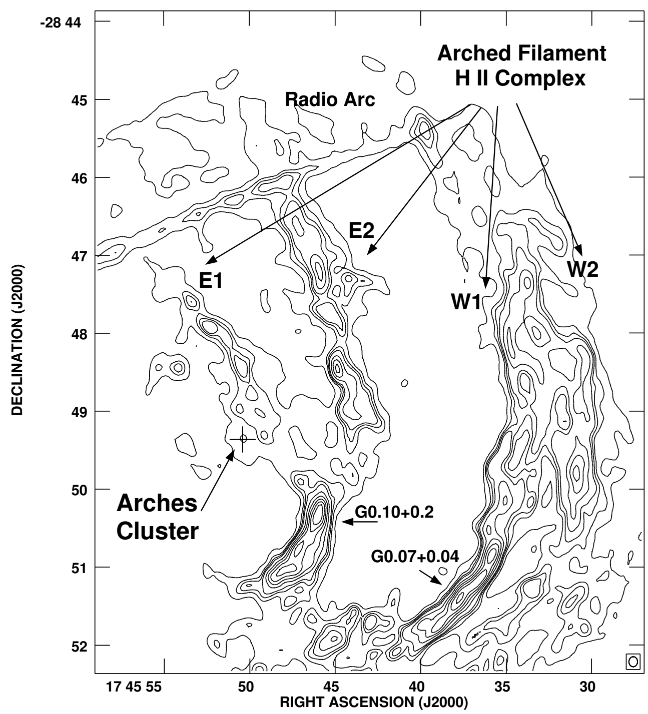

Figure 1: Location of Arches stellar cluster and the surrounding Arched Filament H II regions and the linear magnetic filaments in the Radio Arc. The contours represent VLA 8.5 GHz continuum emission at levels of 7.5, 15, 20, 25, 37.5, 50, 75, and 87.5 mJy beam^{-1}, with a resolution of $7''.8 \times 6''.6$, PA = $-0^\circ.7$, from Lang et al. (2001a).

2 Radio studies of the Arches cluster region

2.1 Ionization and kinematics of surrounding medium

Figure 1 shows that the Arches cluster is located at essentially the center of curvature of the Arched Filament H II regions (one of the sets of thermal radio filaments in the Radio Arc). High resolution radio continuum studies of the Arched Filaments made with the Very

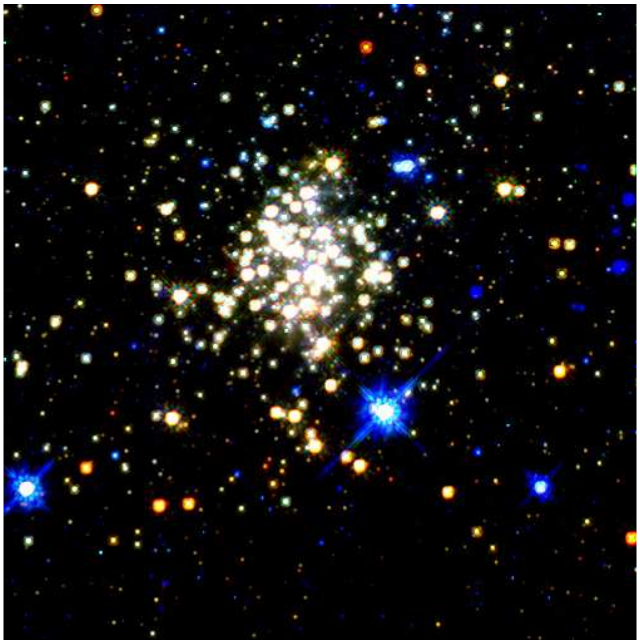

Figure 2: *HST* NICMOS JHK composite image of the Arches cluster from Figer et al. (1999). The scale of each side represents $\sim$ 5 ly or 1.75 pc.

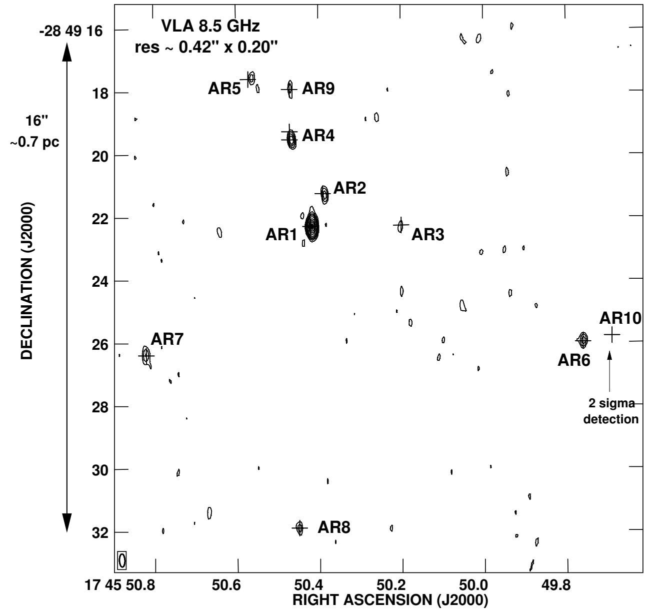

Figure 3: VLA 8.5 GHz image of the Arches cluster. The rms level of 25 μJy beam^{-1} and the crosses represent the positions of mass-losing stars (Figer et al. 2002).

Large Array (VLA) of the National Radio Astronomy Observatory show that the number of ionizing photons produced ($\sim 4\times10^{51}$ photons s^{-1}; Figer et al. 2002; Fig. 2) can easily account for the radio continuum flux density of the entire set of filaments ($\sim 4\times10^{50}$ photons s^{-1}; Lang et al. 2001a). Therefore, the thermal Arched Filaments near the GC can be understood to represent the ionized edge of large, dense molecular cloud located in this region. The velocities of both ionized and molecular gas are counter to Galactic rotation (~ -70 to +10 km s^{-1}) for their radius and most likely represent gas moving on highly non-circular orbits (Lang et al. 2002). In addition, the Arches cluster did not likely form out of the molecular cloud as the tidal forces in the GC region would destroy a cloud in a timescale less than the age of the stellar cluster ($\tau_{\rm cluster}$ $\sim$ 2 Myr) (Lang et al. 2001a). Instead, it is thought that the Arches cluster is ionizing the outer edge of an infalling or passing-by molecular cloud close to the GC. This model differs from more classical star-forming regions where a star (or cluster) is ionizing the inner regions (or edges) of its dense parental cloud (as in the galactic starburst NGC3603), but produces observationally the same signatures of massive star-forming activity.

2.2 Detections of individual stellar winds

The massive luminous members of the Arches cluster have been roughly classified to be a combination of OB-type stars as well as a number of highly-evolved stellar types, including WR stars (Figer et al. 2002). Such massive stars should be losing mass from their surfaces at fairly high rates (10^{-5} to 10^{-4} $M_\odot$ yr^{-1}) in the form of stellar winds. High-resolution centimeter-wave radio studies can detect the stellar wind emission from individual stars. VLA observations of the center of the Arches cluster have been made at $0.5''$ resolution at 8.5 GHz and show at least 10 compact radio sources (see Fig. 3), all of which are associated with massive stars (near-IR sources) known to have stellar winds (Lang et al. 2001b; Lang et al., *in prep*). Based on the spectral indices of these sources (α = +0.3 to +0.9) and their positional coincidence with massive stars, the compact radio sources are interpreted to be detections of the stellar winds. The flux densities can be converted into mass-loss rates for the stellar winds in the Arches, resulting in values which range from 2–17×10^{-5} $M_\odot$ yr^{-1}. Several of the compact sources have slightly flatter (or even negative) spectral indices than the canonical α = +0.6 for $S_\nu \propto \nu^\alpha$. These sources are thought to have a non-thermal component to their wind emission, which may be related to a shock caused

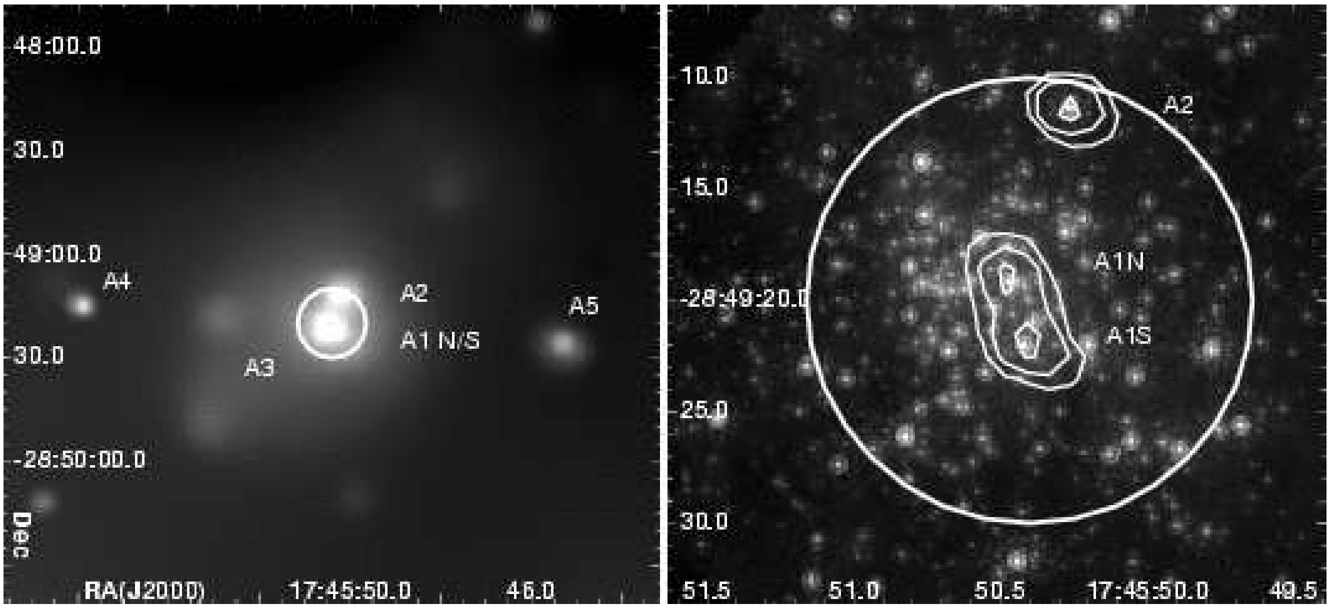

Figure 4: (left) The smoothed *Chandra* data showing the X-ray emission in the vicinity of the Arches cluster, both point-like (A1 N/S and A2) and more diffuse (A3) (data from Yusef-Zadeh et al. 2002). (right): X-ray contours of A1 N/S and A2 overlaid on the *HST* NIMCOS image, showing the correspondence between X-ray sources and individual mass-losing stars from Law & Yusef-Zadeh (2003).

by colliding winds in binary systems (Williams et AP. 1997).

3 X-ray studies of the Arches cluster region

Chandra observations of the GC Radio Arc and the entire central 300 pc of the Galaxy show that the Arches cluster is one of the brightest X-ray sources (Yusef-Zadeh et al. 2002; Wang, Gotthelf & Lang 2002). The X-ray emission is made up of both point-like sources and also a diffuse component. Yusef-Zadeh et al. (2002) identify three point sources in the center of the Arches cluster (A1 N/S, and A2). Figure 4 shows the smoothed X-ray emission near the center of the Arches cluster. The power-law X-ray spectra and positional coincidence of the X-ray point sources with radio stellar wind sources (Law & Yusef-Zadeh 2003) suggest that these may be detections of massive X-ray binary sources (Yusef-Zadeh et al. 2002). It is not possible to determine whether the stellar sources are binaries from the current resolution of the near-IR observations. However, similar concentrations of radio and X-ray sources are seen in the centers of the clusters in the galactic starburst region NGC3603 and at the core of the LMC's R136 cluster and indicate the presence of X-ray binary sources (Moffat et al. 2002; Portegies-Zwart et al. 2002). The diffuse component of X-ray emission (A3) has been interpreted in the context of a "cluster outflow" of shocked gas from multiple X-ray binary wind-wind collisions at the core of the Arches cluster (Canto et al. 2000; Raga et al. 2001; Yusef-Zadeh et al. 2002).

4 Xraydio studies of the Arches cluster

A number of recent studies of the Arches cluster environment have been inspired by synthesizing results from X-ray and radio observations. These are briefly highlighted in the following sections.

4.1 Non-thermal diffuse radio emission

As reported above (Sect. 2.1) high-resolution radio observations have revealed a number of compact radio sources, mainly thermal in nature and directly associated with individual mass-losing stars (Lang et al. 2001b). On slightly larger scales ($\sim 12''$, or ~ 0.4 pc at the GC), a diffuse radio source has been discovered at $\nu = 330$ MHz which has a non-thermal nature, based on observations at four frequencies with the VLA (Yusef-Zadeh et al. 2003). This diffuse radio source is interpreted as a result of colliding wind shocks of the cluster flow which generate relativistic particles that are due to diffuse shock acceleration.

4.2 Non-thermal stellar wind emission

Both the slightly flattened spectral index of several of the compact radio sources in the Arches cluster and the presence of diffuse non-thermal radio emission indicate that there may be non-thermal stellar wind emission present in the cluster. This type of emission is usually attributed to a wind-wind collision in a massive binary system. Therefore, a detection of one of these wind sources with the Very Long Baseline Array (VLBA) would confirm that the flattened indices are due to a non-thermal component and that the Arches cluster may have binary members. In addition, with VLBA astrometry, there is the potential in future epochs to study the proper motion and to determine the distance and dynamics of the cluster. This study is currently underway by Lang & Bower (BL121).

4.3 Nature of the diffuse 6.4 keV X-ray emission?

Although the X-ray diffuse emission surrounding the Arches cluster may be associated with a "cluster outflow" (see Sect. 3), it exhibits a very prominent 6.4 keV emission line in its spectrum (Yusef-Zadeh et al. 2002). In general, the origin of 6.4 keV emission in the GC region is not well understood, but a main feature of this emission is its close correspondence to the dense molecular clouds through the central 100s of pc. Koyama et al. (1996) and several others (e.g., Murakami et al. 2000) have suggested that regions of diffuse 6.4 keV emission represent "X-ray reflection nebulae", in which a hard X-ray outburst of Sgr A* generates iron fluorescence in dense molecular material within the central region. Another alternative is that low-energy cosmic ray electrons cause the 6.4 keV emission locally (Yusef-Zadeh et al. 2002b). High-resolution investigations between the molecular gas in the vicinity of the Arches and the diffuse 6.4 keV emission are underway to explore the nature of the 6.4 keV emission (Lang & Wang, *in prep*).

5 Summary

In short, the combination of near-IR, radio and X-ray observations of the Arches cluster and its surrounding environment have revealed a wealth of new information on the impact of the Arches cluster in the GC. Overall, the energetics of this region appear to be dominated by activities related to massive star clusters, as evidenced by the correspondence between diffuse X-ray emission and the signposts of massive star activities (radio continuum and mid-IR emission (from the Mid-course Space Experiment, MSX) in the central 300 pc of the GC (Wang, Gotthelf & Lang 2002). The Arches can therefore serve as an important analog for this activity in our GC and in other nearby starburst regions.

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