Young Stellar Clusters, WR-type Phenomenon and the Origin of the Galactic Center Nonthermal Radio Filaments

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Abstract.

Recent observations of the Arches cluster located within a projected distance of 30 pc from the dynamical center of the Galaxy have shown the presence of diffuse and discrete X-ray continuum emission, diffuse 6.4keV line emission as well as thermal and nonthermal radio continuum emission. This young and dense stellar cluster is also recognized to be within the 95% error circle of an identified steady source of γ-ray emission associated with the EGRET source 3EG J1746–2851. Much of the thermal and nonthermal emission can be explained by shocked gas resulting from colliding winds originating from massive binaries within the cluster. In particular, we argue that nonthermal particles could upscatter the radiation field of the cluster by ICS and account for the γ-ray emission. We also consider that the fluorescent 6.4 keV line emission may be the result of the impact of low-energy relativistic particles on neutral gas distributed in the vicinity of the cluster. Lastly, we sketch an interpretation in which young stellar clusters and massive young binary systems are responsible for the origin of nonthermal radio filaments found throughout the inner 300pc of the Galaxy. The collimation of the nonthermal filaments may be done in the colliding wind region by the ionized surface of individual mass-losing stars of massive binary systems. In this picture, a WR-type phenomenon is expected to power a central star burst in the Galactic center in order to account for all the observed filaments.

1. Introduction

One of the most important results of recent studies of the Galactic center is the revelation of a large concentration of dark matter which is coincident with the bright compact radio source Sgr A* (Schödel et al. 2003; Ghez et al. 2003). Another important result is the discovery of three clusters of young, massive stars within the projected distance of 30 pc from the Galactic center. These objects are not run-of-the-mill clusters in the Galaxy and it is remarkable that three such young and compact systems are found in a small volume of the Galaxy. This region is known for its high extinction and source confusion and star formation has to overcome the strong tidal effect in this high pressure environment. These high density stellar clusters consist of mainly O and WR stars with individual stellar masses greater than 20 $M_\odot$ as their winds should affect their surrounding interstellar environment. Here, we focus on the Arches cluster, the densest and possibly the youngest of these systems. This cluster provides an excellent laboratory to study thermal and nonthermal processes operating in a small volume.
The other two clusters are the Quintuplet and the central Sgr A clusters, as discussed by D. Figer and A. Ghez in these proceedings.

The young clusters such as the Arches cluster can be identified not only by near-IR wavelength technique but also in X-rays and radio wavelengths. In X-ray regime, clusters can be detected by their hot thermal X-ray emission due to wind-wind collision in binary systems whereas in high frequency radio regime, a cluster of free-free emitting sources are identified with ionized stellar winds. Nonthermal radio emission at low frequencies may be another method of detecting dense stellar clusters. The production of relativistic particles in dense stellar clusters as well as OB-WR binary systems have important consequences in the chemistry of interstellar clouds in the vicinity of the cluster. Here we argue that dense stellar clusters and WR-OB binary systems are seeds of relativistic particles that can be responsible for production of nonthermal radio filaments observed throughout the Galactic center.

1.1. The Arches Cluster G0.12+0.02

X-ray Emission The Arches cluster consists of about 150 O star candidates with stellar masses greater than 20 M⊙ (Figer et al. 1999). This cluster is ∼ 15″ across, with an estimated density of 3 × 10⁶ M⊙ pc⁻³ within its inner 9″ (0.36 pc) (Cotera et al. 1996; Serabyn, Shupe & Figer 1998). It is the densest known stellar cluster in the Galaxy, denser than R136, the central cluster of 30 Dor in the LMC. The age of the Arches cluster is estimated to be 1-2 Myrs (e.g. Figer et al. 1999). X-ray emission from the Arches cluster has recently been detected using Chandra observations (Yusef-Zadeh et al. 2002; Law and Yusef-Zadeh 2004). These observations identify two bright compact sources A1S, A1N lying at the core of the cluster and one source A2 lying at the boundary of the cluster about 10″ away from the core. These sources coincide with mass-losing WN/Of stars. The spectral analysis of individual sources A1N, A1S and A2 give fit values of temperatures < 2.3 keV. The spectra of the sources from the inner 15″ of the core may be fit with a two-temperature absorbed model (Yusef-Zadeh et al. 2002) or a single temperature and a power law (Law and Yusef-Zadeh 2004). The quality of each fit is essentially the same, as measured by χ² statistics, however, the unabsorbed flux and the photon index from the power-law component are very difficult to constrain. The unabsorbed X-ray luminosity from the core of the cluster ranges between 0.5 and 3×10³⁵ erg s⁻¹ depending on which spectral fits have been used.

One of the most interesting result coming from X-ray observations of the Arches cluster is the detection of extended emission surrounding the cluster. This large scale diffuse ovoid feature (A3) with dimensions of approximately 90″ × 60″ (3.6 × 2.4 pc) extends well beyond the edge of the cluster, which is < 15″ in diameter. Theoretical work studying the nature of X-ray emission from the collision of stellar winds in a dense cluster environment such as the Arches cluster predicts a cluster wind escaping from the outer boundary of the cluster (Cantó et al. 2000, Raga et al. 2001). These authors consider that shocked gas arising from stellar winds is in the form of discrete X-ray sources as well as diffuse X-ray emission, the so-called “cluster wind”. More recently, Rockefeller et al. (2004) have calculated simulations of X-ray luminosities from the Arches cluster where both diffuse and compact X-ray sources have been
accounted for by wind sources with a varying degree of mass-loss rates. It is possible that the continuum extended emission is due to the “cluster wind” as predicted theoretically.

Extended 6.4 keV line component is also detected. The spectrum of the extended source A3 can be fitted by a single thermal bremsstrahlung and an additional Gaussian contributed by fluorescent Fe Kα 6.4 keV line. The nature of diffuse 6.4 keV emission is not clear. This diffuse component associated with A3 may be produced by the scattering of radiation from an adjacent molecular cloud. The irradiation of the cloud may also contaminate the “cluster wind” emission which is expected to be extended. The true distribution of scattered radiation and the cluster wind emission is a difficult task that should be done in future sensitive measurements. The source of hard X-ray emission responsible for irradiation of the cloud could be the Arches cluster itself or perhaps Sgr A* assuming that it has been active in the past. An alternative model is that the impact of low-energy cosmic rays produces the 6.4 keV line and continuum emission from A3. The relativistic particles needed for this mechanism could arise from the wind-wind collision from the cluster itself, as discussed below. It has recently been demonstrated that bremsstrahlung from low-energy cosmic-ray electrons can naturally explain the spectrum below 10 keV as well as the strength of the Fe 6.4 keV line emission (Valinia et al. 2000). This model has been applied successfully to a dense molecular cloud G0.13-0.13 near the Galactic center (Yusef-Zadeh et al. 2003).

**Radio Emission** Radio continuum emission from a cluster of nine stellar sources AR1-9 has recently been detected toward the Arches cluster (Lang et al. 2001). The radio spectra and near-IR spectral type of the cluster of eight radio stars are consistent with ionized stellar winds arising from mass-losing WN and/or Of stars with mass-loss rates ranging between $3 \times 10^{-5}$ to $1.7 \times 10^{-4} M_\odot \text{yr}^{-1}$ (Lang et al. 2001). Free-free emission resulting from ionized stellar outflow has a positive spectral index ($F_\nu \propto \nu^{0.6}$; Panagia & Felli 1975). With the exception of AR6, all sources show a spectrum ranging between $\alpha$=0.3 and 0.9. The X-ray sources A1N and A1S at the core of the cluster coincide with ionized stellar wind sources AR1 and AR4, respectively (Lang et al. 2001). Interestingly, both these bright early type stellar sources are variable in radio wavelengths (Lang 2003).

More recently, radio observations of the Arches cluster indicate nonthermal emission from this cluster at 327 MHz (Yusef-Zadeh et al. 2003). The high frequency radio emission from the cluster is compact and arises from mass-losing stellar sources, whereas the low-frequency radio emission appears to be diffuse with nonthermal characteristics. The evidence for nonthermal emission at radio wavelengths strengthens the single temperature and power-law fit model to the X-ray emission from the inner 15″ of the Arches cluster as discussed above.

**γ-ray Emission** The existence of nonthermal particles within the core of a luminous young stellar cluster suggests the possibility that the nonthermal X-ray or γ-ray emission could result from upscattering of the radiation field with a luminosity of $10^{38}$L_⊙ by nonthermal particles (Ozernoy, Genzel & Usov 1997; Yusef-Zadeh et al. 2003). In fact, the Arches cluster is displaced only by ≈ 200″ from the nominal position of the unidentified EGRET source 3EG J1746-2851.
(Hartman et al. 1999), located well within the 95% error radius of 0.13\(^0\). This steady and strong \(\gamma\)-ray source has a photon index 1.7 and a flux of \(1.2 \times 10^{-6}\) photons cm\(^{-2}\) s\(^{-1}\) with energies greater than 100 MeV. The \(E^{-1.7}\) photon spectrum of 3EG J1746–2851 could be produced by inverse Compton scattering from a distribution of relativistic electrons. The spectral index of \(\alpha=0.7\) is consistent within the uncertainty of the spectral index value of nonthermal radio emission from the Arches cluster (Yusef-Zadeh, Law and Wardle 2003).

1.2. Discussion

Colliding Wind Binaries  Radio and X-ray observations of the Arches cluster provide the evidence for interacting binary systems within the cluster. The strongest argument in favor of such a suggestion comes from the variability of radio emission from stellar sources at high frequencies (Lang 2003). The variable radio sources AR1 and AR4 coincide with the peak of X-ray emission A1S and A1N at the core of the cluster. Radio emission from binary stars could vary between fully thermal and nonthermal spectrum and many WR-OB binary systems have displayed this characteristic (e.g., Chapman et al. 1999). Additional support comes from the nonthermal spectrum of AR6 and the nonthermal extended emission from the cluster, both of which are unlikely to be produced by single stars. Yet another reason for the suggestion of binary systems within the cluster comes from high X-ray luminosity of discrete sources as well as a high ratio of X-ray to radio flux for individual sources. These ratios are more consistent with those of known WR-OB binary systems (Chapman et al. 1999)

Nonthermal Radio Emission  One of the most intriguing aspects of radiative properties of the Arches cluster is the detection of low-frequency nonthermal emission at 327 MHz. One of the candidates for production of nonthermal emission is colliding wind binaries within the cluster. However, free-free absorption in these sources will not allow nonthermal radiation to escape from the photosphere radius of individual members of WR-OB stars with optical depth of 1 at 327 MHz. For example, the photospheric radius of an O star wind is more than \(10^4 R_\odot\) which is as large as the size of the binary system. Other effects that are also important to suppress the emission at low frequencies are synchrotron self-absorption and Razin effect (Dougherty et al. 2003; Pittard in these proceedings). The fact that nonthermal low-frequency emission has been detected suggests that neither of these effects may be important. Deatiled theoretical work by Dougherty et al. (2003) suggests that the ratio of relativistic to thermal energy density is critical for suppression of low-frequency emission due to synchrotron self-absorption and Razin effects. However, if the the relativistic energy density as well as the maximum energy of relativistic particles \(\gamma\) are high enough, neither Razin nor synchroton self-absorption can be important. This implies that the acceleration of particles, whatever the mechanism (e.g., Fermi acceleration, reconnection) is very efficient in these systems. Alternatively, the nonthermal emission may arise from the contribution of the cluster wind being shocked at the interface between the stellar cluster and the dense ISM. Another contribution to explain the origin of low-frequency radio emission is that the emission arises from the colliding winds between individual members of the cluster. The average separation of stars within the cluster is larger than the O star photospheric radius of optical depth 1 at 327 MHz. The evidence for diffuse
nonthermal emission at 327 MHz from the Arches cluster is not inconsistent with this picture.

**Nonthermal Radio Filaments**

Over the last two decades a large number of radio observations have shown the existence of dozens of systems of filamentary structures within the inner two degrees of the Galactic center (e.g., Nord et al. 2004; Yusef-Zadeh, Hewitt and Cotton 2004). Their transverse filament dimensions are 0.1 to 1 pc (2″ to 20″ at the distance of the Galactic center) and their length is on the order of tens of parsecs. Their strongly linearly polarized emission plus their radio spectral index distribution suggest a nonthermal synchrotron origin. Recent observations indicate that the longest and most prominent filaments run roughly perpendicular to the Galactic plane (> 5′) whereas the short filaments do not show a preferred orientation perpendicular to the Galactic plane.

One of the motivations for the hypothesis that nonthermal radio filaments near the Galactic center originate from dense clusters of massive stars comes from recent radio surveys indicating that many of the radio filaments are concentrated in the vicinity of star forming regions. The other motivation is the revelation that nonthermal particles are easily generated by colliding winds of massive young binaries. The idea of stellar acceleration of particles to relativistic energies was originally set forth by Rosner and Bodo (1996) in order to explain the origin of nonthermal filaments. Unlike many other models of the Galactic center filaments, this idea was able to explain the transverse dimension of the filaments by matching it with the size of the wind bubble created by winds of mass-losing stars. This idea was recently expanded by suggesting that nonthermal emission from the Galactic center filaments originates from the shocked region of the colliding stellar winds of young clusters (Yusef-Zadeh 2003). The evidence for the generation of nonthermal particles which are accelerated by young massive binary systems is overwhelming. In fact, numerous WR-type stars are found in the three young clusters in the Galactic center region. Based on a high fraction of massive stars found in binary and multiple systems, we provided evidence that these systems are also distributed within the Arches cluster. More recently, the nonthermal filaments have been interpreted in terms of jets launched by embedded stars or clusters as they extract mass and energy propagating in a dense ISM of the Galactic center region (Yusef-Zadeh and Königl 2004).

Theoretically, the key issue is to explain the highly collimated nature of nonthermal filaments in the context of a jet model launched from massive binaries and dense clusters. In this schematic model, we suggest that the wind collision region is the site of acceleration of relativistic particles in a close binary system. We assume that the dense stellar clusters are at their earliest phase of evolution when they are most compact containing WR-OB binary systems whose members orbit each other with a short period. The colliding wind region lies at a distance where the winds have gained their terminal speeds. Stars within the binary system are so close to each other that the surface of the ionized winds from individual stars deviates from spherical geometry due to tidal effects. In this picture, the radial density distribution of ionized wind does not follow \( r^{-2} \) and the colliding wind region has an angular dependence in the orbital plane where mass-loss has an angular dependence (e.g., Friend and Castor 1982). The
The strongest synchrotron emissivity is expected to be along the axis where the wind velocity and density are highest. In the case where there is spherical symmetry, the intrinsically synchrotron emissivity from the wind collision site depends on $D^{-1/2}$ where $D$ is the binary separation (Dougherty et al. 2003). The relativistic particles generated at this site are expected to be advected by the high pressure thermal gas as they run perpendicular to the orbital plane and form jet-like structures. A recent study of SS443 suggests that WR-type phenomena are responsible for the collimated jet of well-known systems (Fuchs in these proceedings). We propose that the distorted surface of the ionized winds from individual WR stars, as shown schematically in Figure 1, acts as a wall that collimates nonthermal gas along the direction perpendicular to the orbital plane of a close binary system. We speculate that the most prominent nonthermal filaments are expected to be associated with the early phase of very dense massive clusters whereas the faint and short filaments are accounted for by isolated massive binary systems. In both scenarios, the filaments are expected to be located in the vicinity of young stellar sources with X-ray counterparts. Due to strong effects of synchrotron self-absorption, Razin and free-free absorption, radio emission from the region where the filaments originate are expected to be weak. If this picture is correct, a large number of hidden WR-OB binaries and young clusters are required to explain numerous filaments found in the Galactic center region. Such a large number of massive young stars and clusters in a small volume implies a starburst activity in the nucleus of the Galaxy. This is not inconsistent with recent ISO measurements of the excitation condition of the Galactic center region suggesting a low-excitation starburst activity (Rodriguez-Fernandez and Martin-Pintado 2004). Additional support for a powerful starburst activity in the last several million years comes from large-scale Galactic winds in this region (Bland-Hawthorn and Cohen 2003). A more detailed account of this model will be given elsewhere.

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2. References

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Figure 1. A schematic diagram showing the geometry of the colliding wind region in a close binary system where the surface of ionized wind is asymmetric by tidal and centrifugal effects. For simplicity, both mass-losing young stars are assumed to have the same spectral type. The outflow representing a galactic center filament consists of relativistic particles produced by wind-wind collision and is collimated by the surface of the ionized winds from the mass-losing stars.
