Presented at a NATO adv. School "The Nuclei of Normal Galaxies: Lessons from the Galactic Center", Ringberg Schloss, Tegernsee, 1993 July 25 - 30.

LARGE-SCALE RADIO STRUCTUERS IN THE GALACTIC CENTER

Yoshiaki SOFUE
Institute of Astronomy, University of Tokyo
Mitaka, Tokyo 181, Japan
sofue@sof.ioa.s.u-tokyo.ac.jp

Abstract. Radio continuum observations of the galactic center region have revealed a number of vertical structures running across the galactic plane. Most of the vertical structures are reasonably attributed either to poloidal magnetic field or to energy release toward the halo. The relation of the continuum structures to the molecular gas rings and their vertical extension are also discussed. Some large-scale ejection features appear to have similarity to bubbles found in external galaxies.

Keywords: Galactic center; Radio emission; Jets; Magnetic field

1. Introduction

Radio continuum features in the galactic center region are a superposition of star-forming regions, which comprises a thin thermal disk, and vertical structures, which are mostly nonthermal closely related poloidal magnetic fields. The radio emission is therefore a mixture of thermal and nonthermal emissions. In this paper we review radio continuum observations of the galactic center with a particular regard to large-scale extended features (larger than a few tens of pc). We first discuss the properties of the radio emission, reviewing the methods to distinguish thermal and nonthermal emissions. We then summarize various exotic structures, which are mostly perpendicular to the galactic plane, and discuss them in relation to vertical magnetic fields and to manifestation of energy release from the nuclear disk. We comment on the similarity of large-scale ejection features to some radio bubble features in external galaxies. Vertical cylinder structures of expanding rings of molecular gas are also discussed.

The galactic center region has been mapped in the radio continuum at various frequencies: some of typical surveys have been made at 80 MHz (LaRosa and Kassim 1985); 160 MHz (Dulk and Slee 1974; Yusef-Zadeh et al); 327 MHz (Yusef-Zadeh et al); 408 MHz (Little 1974; Haslam et al 1982); 610 MHz (Downes et al 1978); 843 MHz (Mills and Drinkwater 1984); 1.4 GHz (Yusef-Zadeh et al 1984; Liszt 1986; Reich et al 1990); 2.7 GHz (Reich et al 1984); 5 GHz (Altenhoff et al 1979); 10 GHz (Pauls et al 1976; Handa et al 1987; Seiradakis et al 1985, 1989; Haynes et al 1993);

15.5 GHz (Kapitzky and Dent 1974); 32 GHz (Reich 1993); 43 GHz (Sofue et al 1986); 91 GHz (Tsuboi et al 1988). There have been various reviews, some which are by Lo (1986); Brown and Listzt (1984); Genzel and Townes (1987); Sofue (1989).

2. Radio Continuum Emission

The radio continuum emission from the galactic center region of $\sim 3^\circ \times 3^\circ$ is a mixture of nonthermal (synchrotron) and thermal (free-free) emissions. In order to investigate the various observed structures it is essential to clarify their emission mechanisms. We describe the methods to separate these two emission components.

2.1 Flat Radio Spectra

The conventional method to investigate the emission mechanism is to study the spectral index. Thermal emission shows a flat spectrum of $\alpha = -0.1$ with $S \propto \nu^\alpha$, while nonthermal emission usually shows steeper spectrum. Mezger and Pauls (1979) studied radio emission from the galactic center, and concluded that the extended component comprises an ellipsoidal disk of diffuse thermal gas of a size of $\sim 300 \times 100$ pc. However, a spectral index study of radio data in large frequency separation, from 845 MHz to 43 GHz, has shown that the spectral index in the radio Arc and bridge region near Sgr A is flat or even inverted (positive) (Reich et al 1988). It was shown that the spectral index in the central 3° region is almost everywhere flat (Sofue 1985). Flat spectra are obtained even in regions where strong linear polarization was detected (see Reich 1993 in this issue).

Hence, the flat spectrum observed near the galactic center must no longer be taken as an indicator of thermal emission. We note that many active galactic nuclei in extragalactic systems often show flat radio spectra for their nonthermal characteristics. However, the question why the spectra are so flat, or how high-energy electrons are supplied so efficiently in such a wide area of the galactic center, is not answered as yet.

2.2. Linear Polarization

A direct and more convincing way to distinguish synchrotron radiation is to measure the linear polarization. However, an extremely high Faraday rotation caused by the dense interstellar matter and long path length through the galactic plane depolarizes the emission by the finite-beam and finite-bandwidth effects, which makes the measurement difficult. This difficulty has been resolved by the development of a multi-frequency, narrow-band Faraday polarimeter (Inoue et al 1984) as well as by high-resolution and high-frequency observations using the VLA (Yusef-Zadeh et al 1986; Inoue et al 1988). Very large rotation measure ($RM >\sim 10^3$ rad m^{-2}) and high degree (10 - 50%) polarization have been observed along the radio Arc and on the eastern ridge of the Galactic Center Lobe (Inoue et al 1984; Tsuboi et al 1986; Seiradakis et al 1985; Sofue et al 1986; Reich 1988; Haynes et al 1992; Reich 1993).

At high frequencies the Faraday depolarization becomes less effective. Reich (1988; 1993 in this issue) has reported the detection of polarization as high as $p \sim 50$ % along the Arc at mm wavelengths. This is nearly equal to the theretical maximum, $p_{\max} = (\alpha + 1)/(\alpha + 7/3) \simeq 47$ %, for the Arc region where the spectral index has the value of $\alpha \simeq +0.2$. This fact implies that the magnetic field is almost perfectly ordered. This is also consistent with the VLA observations showing straight filaments suggestive of highly ordered magnetic field (Yusef-Zadeh et al 1984; Morris 1993 in this issue) (Fig. 1). From these observations of linear polarization it is clear that the radio emission near the galactic center, in particular around the radio Arc, is nonthermal despite their flat or inverted spectra.

2.3 Infrared-to-Radio Ratio

Separation of thermal and nonthermal radio emission can be done in a more efficient way even for the regions where no polarization data are available. The method uses comparison of far-IR (e.g. 60 μm data from IRAS survey) and radio intensities (both in Jy/str): thermal emission regions, mostly composed of HII gas, have high IR-to-radio ratio, $R = I_{\rm FIR}/I_{\rm R} \simeq 10^3$. On the other hand, nonthermal emission regions, such as supernova remnants, have small IR-to-radio ratio, $R = 0 \sim 300$. Using this characteristics we are able to distinguish thermal and nonthermal emission regions in a wide area near the galactic center (Reich et al 1987). The region near the galactic plane is dominated by thermal emission and many strong radio sources like Sgr B2 appear thermal (HII) (see, e.g., Mezger and Pauls 1979). These regions are closely associated with dense molecular clouds (Bally et al 1987) and therefore related to star formation from the clouds. On the other hand we find many of the prominent features like the Radio Arc, Sgr A and regions high above the galactic plane including the GCL (galactic center lobe) are nonthermal.

3. Three-Dimensional Morphology

The radio continuum mappings have revealed various exotic features of peculiar morphology (Fig. 1). Many of them appear to lie not parallel to the galactic plane, but run perpendicular to the disk, which are most likely related to poloidal magnetic fields.

3.1. The Thermal Disk and Filaments

The nuclear disk about 50 pc thick and 200 pc in radius comprises numerous clumps of thermal emission regions, most of which are active star-forming regions and HII regions, are detected in the hydrogen recombination lines (Mezger and Pauls 1979; Pauls et al 1979). Typical HII regions are named Sgr B, C, D and E. The total HII mass of $2 \times 10^6 M_\odot$ has been estimated, and the production rate of Ly continuum photons of 3×10^{52} s^{-1} is required to maintain this amount of HII gas (Mezger and Pauls 1979). The star formaing rate, which is assumed to be proportional to the Ly continuum photon flux, of the central few hundred pc region reaches almost 10% of the total star forming rate of the Galaxy. The HII regions are surrounded by expanding shells and cylinders of molecular gas (see 4.3).

Besides star formation regions, various exotic thermal structures have been observed: Complex filaments are extending from Sgr A toward the north, composing a bridge between the radio Arc and Sgr A (Yusef-Zadeh et al 1984; Yusef-Zadeh and Morris 1988). Detection of hydrogen recombination lines (Pauls et al 1976; Yusef-Zadeh et al 1986) and the association of molecular gas at negative velocities (Serabyn and Güsten 1986; 1987; Güsten 1989) indicate its thermal characteristics, and the structures are often called the thermal arched filaments.

Despite of thermal radio emission, a large Faraday rotation has been detected toward the bridge, which indicates the existence of a magnetic field along the thermal filaments (Sofue et al 1987). A magneto-ionic jet model in which the gas is flowing out of Sgr A and collides with the ambient poloidal magnetic field at the radio Arc has been proposed (Sofue and Fujimoto 1987). Serabyn and Güsten (1987) argue that the gas is flowing toward the center and an accretion model has been proposed by analysing the velocity field. The complex structure in the bridge indicates high turbulent motion inside the bridge. In fact, velocity dispersion as high as 30-50 km s^{-1}has been observed in the bridge from recombination-line observations (Pauls et al 1976), and it increases drastically near the Arc (60-70 km s^{-1}), which suggests a dynamical interaction of the bridge with the Arc. Yusef-Zadeh and Morris (1988), based on their high-resolution maps, argue that the Arc (straight filaments) and the arched filaments are interacting with each other.

3.2. Vertical Magnetic Tubes: Radio Arc and Threads

The radio Arc was originally found in the radio continuum survey maps of the galactic plane (Downes et al 1978), and has been resolved into many straight filaments with the use of VLA (Morris and Yusef-Zadeh 1987, 1988; Yusef-Zadeh et al 1984; Yusef-Zadeh 1986; 1988; 1989; Morris 1993 in this issue) (Fig. 1). The straight filaments run perpendicular to the galactic plane, and extend more than $\sim$ 100 pc toward positive latitudes. The mid point of the arc is strongly polarized ($\sim 20 - 50$ %), and shows a high Faraday rotation ($RM \sim$ a few $10^3 - 10^4$ rad m^{-2}) (Inoue et al 1984; Tsuboi et al 1986; Sofue et al 1987; Yusef-Zadeh and Morris 1988; Reich 1988; Reich 1993). The theoretically maximum polarization of 50% along the Arc (Reich 1993) indicates a highly ordered magnetic field and is consistent with the VLA straight filaments. The magnetic field direction, as detemined from the intrinsic polarization angles, is parallel to the filaments and vertical to the galactic plane. Field strength as high as $\sim$ 1 mG has been estimated in the Arc and in some radio filaments (e.g., Morris 1993).

Interferometric observations of the filaments in the Arc at 43 GHz revealed that some filaments are not visible at this high frequency. Assumeing the field strength of the order of 1 mG, we could estimated the life time of cosmic-ray electrons emitting at 43 GHz to be about 4000 years (Sofue et al. 1992). This implies that the filaments of strong magnetic field may be a time variable, or trasient feature, being temporary illuminated by recently accelerated high-energy electrons. It would be, therefore, interesting to perform a time-variation watch of the thin nonthermal filaments in the Arc by high-resolution VLA observations.

The higher latitude extensions of the Arc, both toward positive and negative latitudes for more than 100 pc, are also polarized and are called polarized plumes (Tsuboi et al 1986; Yusef-Zadeh and Morris 1988). The degree of polaraization reaches as high as 20% at 10 GHz. The magnetic field directions are parallel to the radio arc, or vertical to the galactic plane. High Faraday rotation ($\sim \pm 10^3$ rad m^{-2}) has been detected (Tsuboi et al 1986; Sofue et al 1987). The sense of rotation measure reverses from positive to negative latitude sides, indicating a reversal of the line sight component of the magnetic field above and below the galactic plane. The field strength is estimated to be 10-100 μG. Sofue et al (1986) suggest that the polarized spot and the plumes are parts of a large-scale poloidal magnetic field twisted by the disk rotation (see next section).

Besides the filaments in Arcs, numerous straight filaments, called "threads", are observed. They appear to be distributed rather independently of the other major radio sources (Morris and Yusef-Zadeh 1985; Yusef-Zadeh 1988, 1989; Morris 1993).

They are roughly perpendicular to the galactic plane. The threads intersect the other features without interaction. From the very thin and straight appearence the threads are likely magnetic structures, and the vertical nature is consitent with a large-scale poloidal field in the central region (Morris 1993).

3.3. Large-Scale Ejection: Lobes and Jets

The galactic center lobe (GCL) is a loop structure of about 200 pc diameter extending vertically over the galactic plane (Sofue and Handa 1984; Sofue 1985; Fig. 1). The cross section of the lobe parallel to the glactic plane indicates its cylindrical structure. The eastern ridge of the lobe is an extension from the radio Arc and is strongly polarized. The magnetic field is shown to run parallel to the ridge. The ridge also extends toward negative latitude, where a symmetric polarized plume is found. The western ridge emerges from Sgr C and is clearly the extension of the VLA filament. Yusef-Zadeh (1988) reports the detection of filament and polarization in the western ridge, indicating the existence of magnetic field. Recently, Uchida et al (1993) found a complex of molecular gas and warm dust associated with the western ridge of the lobe. They identified a velocity jump in the CO-line spectra with a shock front coinciding with the western ridge. By pointing out that the western ridge has a different characteristics from that of the eastern ridge, Uchida et al (1993) suggest that both ridges might be independent objects.

Formation of the lobe structure has been moldeled in various ways: An explosion hypothesis requires an explosive energy injection near the nucleus, which produces an expanding propagating the disk and halo (Sofue 1984). An MHD acceleration model in which the gas is accelerated via a twist of poloidal magnetic field by the accreting gas disk has been proposed (Uchida et al 1985; Uchida and Shibata 1986).

On a much larger scale of a few kpc above the galactic plane, a giant spur has been found, which emanates from the galactic center toward positive latitude, $b \sim 25^\circ$ (Sofue et al 1988) (Fig. 2). A ridge connecting the spur to the galactic center has been detected by 1408 MHz observations (Sofue et al 1988). This feature, which is 4-kpc long and some 200-pc in diameter, may be cylindrical in shape and extends roughly perpendicular to the galactic plane. This structure might be a jet (or the remnant of a relativistic beam from the nucleus), or it might be magnetic tornado produced by the differential rotation between the halo and the nuclear disk. Recently, Krichbaum et al (1993) found a VLBI mini-jet in the central few mas region of Sgr A^* at 43 GHz. The jet direction appears to point the largest scale jet at high latitude, and they have suggested a possible connection of both objects. Falcke et al (1993) modeled the mini jet and suggested that the 4 kpc-scale jet might be a smoke of a past similar jet phenomenon at the nucleus.

3.4. The North Polar Spur and its similarity to Extragalactic Bubbles

The whole sky radio map at 408 MHz (Haslam et al. 1982) shows numerous radio spurs. The most prominent spur is called the North Polar Spur (NPS), which traces a giant loop on the sky of diamter about 120°, drawing a huge Ω over the galactic center (Fig. 2). There have been various interpretations of this prominent feature, particularly related to a nearby supernova remnant. Here, we comment on a rather exotic idea, which presumes an explosion at the galactic center: The giant Ω-shape of the NPS could be a shock front due to a gigantic explosion or a sudden energy input at the galactic center of the order of $10^{55} \sim 10^{56}$ erg (Sofue 1984). In this model, the NPS must lie at a distance of a few kpc away. On the other hand, the current supernova remnant hypoethesis predicts a distance of a few tens of pc. A key to explore the distance is the X-ray absorption by the galactic disk. If it is a galactic-scale bubble beyond the HI disk, the X rays must be absorbed near the galactic plane: the optical depth (H column density) changes as a function of cosec b. On the other hand, if the NPS is a local object embedded in the galactic HI disk, the optical depth does not change with b, and hence, the NPS ridge should be visible even near the galactic plane at $b < 10^\circ$ where the radio brightness is the highest. In this context, the ROSAT data are most important (Predehl 1993).

Similar huge bubbles in radio cotninuum have been found in many spiral galaxies (Fig. 2): Edge-on galaxy NGC 3079 has S-shaped double lobes which extend for 3 kpc size in both directions of the galactic plane (Duric et al 1983). NGC 4258 is known for its symmetrical S-shaped radio features perpendicular to the major axis (van Albada 1980). These bubbles would look like similar to the NPS if the observer is sitting inside the galaxies.

4. Origin of Vertical Structures

4.1 Poloidal fields

Polarization observations of the galactic center region show that the field direction projected on the sky along the radio Arc and the eastern ridge of the galactic center lobe is perpendicular to the galactic plane (Yusef-Zadeh et al 1984, 1989; Inoue et al 1984; Tsuboi et al 1986; Sofue et al 1987; Reich 1993). Haynes et al (1992) stressed that the polarization is visible in a wider area of $1.5^\circ \times 1.5^\circ$ area around Sgr A, and showed that magnetic field is widely distributed in the galactic center region. Measurements of the Faraday rotation show that the rotation measure (RM) reverses from the lower side of the galactic plane to the upper side, indicating reversal of the line-of-sight component of the field. The reversal of the RM is also observed across the rotation axis of the Galaxy. From these, a poloidal field model has been proposed in which the field lines are twisted by the disk rotation (Sofue and Fujimoto 1987). However, it is often claimed that the very straight nature of the filaments in the radio Arc is suggestive of a field lines not bending. If this is the case, the Faraday reversal should be attributed to intervening fields between the Arc and the Sun. Since the RM reversal happens in $\sim 10'$-scale and the RM amplitude is as large as $RM \sim 10^4$ rad m^{-2}, it is reasonable to suppose that the Faraday effect occurs in the nuclear disk.

If we stand on the primordial origin hypothesis of galactic magnetic fields, we should inevitably consider the evolution of the vertical component of the primordial field. The time scale with which a magnetic field component perpendicular to the disk plane diffuses away from the galaxy may be estimated as $\tau_{\rm vert} \sim r^2/lv \sim 10^{11}$ y. Therefore, the vertical component trapped from the intergalactic space can never escape from the galaxy, but is transferred to the central region when the galaxy contraction proceeds. A rough estimation shows that the field strength of the vertical component in the galaxy is proportional to the surface mass density (Sofue and Fujimoto 1987), and a strong vertical field, some 10 μG, is expected to exist in the central 1-kpc region. On the other hand, the disk component parallel to the galactic plane annihilates in the central region more efficiently than in the outer region and a rather weaker disk field is expected there.

This scenario of evolution of the galactic field thus predicts that a vertical field dominates in the central region, while the disk spiral field has the maximum in the outer disk several kpc away from the central region. This is consistent with the fact that our Galaxy possesses a twisted poloidal field in the center, while the disk field (parallel to the galactic plane and spiral arms) is strongest at $r \sim 5$ kpc. Similar characteristics have been found in spiral galaxy M31 (Berkhuijsen et al 1987): the central radio source shows polarization consistent with the vertical field. The projected field direction is perpendicular to the major axis, while the disk field, which is a superposition of ring and spiral, has the maximum at $r \sim 10$ kpc.

Given a large-scale poloidal field, which penetrates the rotating dense nuclear disk, twist of the field is inevitable. The twist will then propagate toward the halo, accelerating the gas perpendicular to the disk plane. This will result in a cylindrical outflow of gas and cosmic rays, which will account for the formation of the galactic center lobe (Uchida et al 1985; Uchida and Shibata 1986; Shibata and Uchida 1987). The large-scale poloidal field in the halo will also be twisted by the differential rotation beween the disk and halo gases. The twist will amplify the field strength near the rotation axis, and will be observed as the galactic center jet (or tornado) of 4-kpc length (Sofue et al 1988).

4.2. Explosion

A sudden energy release at the galactic center such as an explosion or a star burst also results in vertical gaseous structurs. In fact molecular and hydrogen line observations of the disk gas exhibit various expanding ring features. We here discuss the possibility that an explosion at the center will produce the vertical structures and examine if the expanding rings in the disk plane are associated with vertical strucures.

An explosion and an energy release in a short time like a star burst at the center of a rotating disk can be theoretically traced by hydrodynamic and MHD codes. A shock wave which is initially spherical expands more rapidly in the direction perpendicular to the disk plane because of the smaller gas pressure and mass in this direction compared to those in the disk plane. Then the shock front attains an Ω shape elongated perpendicular to the disk, mimicking the GCL at some stage (Sofue 1984). Further propagation of the shock front through the nuclear disk has been numerically simulated: Refraction of the shock waves due to the density variation in the disk results in focusing onto a ring of radius about twice the scale height of the disk gas density ($\sim$ 200 pc) in the nuclear disk. Such a ring has been indeed observed as the 200-pc expanding ring as follows.

4.3. Expanding Molecular Cylinders

Expanding ring features of various scales are found in the galactic plane, which are mainly observed in the molecular and hydrogen line emissinos (Kaifu et al. 1972; Scoville 1972; Tsuboi 1988; Sofue 1990, 1991). The molecular expanding ring of 200 pc radius is the most tyipical example, which has a radius of 200 pc and is expanding at a velocity of 50 km s^{-1}. The tangential points to the 200-pc ring on the $l - v$ diagram appear at $l = 1^\circ.6$ and at $l = -1^\circ.2$. Cross sections of the ring in CO emission at these longitudes indicates that they compose walls of 150 pc height perpendicular to the galactic plane with a thickness of about 20 pc. Namely, the expanding ring is a cylinder about 150 pc long (Sofue 1989). The kinetic energy of the expansion motion is of the order of 10^{54} ergs, which is comparable to that involved in the galactic center lobe. The coincidence between the energies in the 200-pc cylinder and the GCL is consistent if the GCL will focus on the ring in the future, and the 200-pc ring is the consequence of the shock focusing of a past GCL some 10^6 y ago.

A cylindrical molecular ring has been also found in the starburst galaxy M82 (Nakai et al 1987). The "200-pc ring" in M82 is thought to be the consequence of an energy release, while far more intense than that in our Galaxy center, by successive explosions of supernovae in the central region of the dense molecular disk, which is followed by a vertical wind of high-temperature gas as well as the formation of an expanding ring and a cylinder. Existence of vertical magnetic field is not known, while the intense nonthermal radio emission suggests field strength as high as some 10 μG.

A more number of cylindrical features in the molecular gas has been identified by Tsuboi (1988), who called them "barrels". Barrels are rings and loops on position-velocity diagrams in the galactic center region with a typical diameter of 30 pc and expanding motion of a few 10 km s^{-1}. A detailed comparative study of radio continuum and CO-line emissions in the central few degrees has revealed many loops and shells of molecular gas which surround HII regions in the nulclear disk and are expanding at a velocity of a few 10 km s^{-1}(Sofue 1990). Typical molecular loops (or shells) are found enclosing Sgr B, Sgr C and Sgr D. Molecular gas and continuum thermal sources (HII regions) appear to avoid each other.

4.4. Infalling-Clouds and "Galactic Sprays"

The energy required to produce many of the expanding shells and cylinders is typically $10^{52} - 10^{54}$ ergs. The energy source could be supernova explosions or explosion at the nucleus. We here suggest an alternative possibility of external energy source to create such vertical structures: These structures could be attributed to infalling gaseous debris from the companion galaxies, LMC and SMC. According to the ram-pressure stripping-and-accretion model of gas clouds in a companion galaxy by its parent's gaseous halo and disk (Sofue 1994), interstellar clouds are stripped and accreted toward the disk of the larger galaxy . If we apply this idea to the Magellanic Clouds and the Galaxy, gas clouds in LMC and SMC are stripped, which soon form the Magellanic Stream, and finally infall toward the galactic disk. If the clouds' orbit is retrograde with respect to the galactic rotation, the clouds hit the nuclear disk, where their sprays would exhibit various vertical ridges and peculiar kinematics. The kinetic energy given to the nuclear disk by a collision of an infalling cloud of mass of $10^6 M_\odot$, a typical GMC, is $\sim 4 \times 10^{53}$ erg for an infalling velocity of 200 km s^{-1}. This energy is enough to produce any of the vertical and dynamical (expanding) phenomena as discussed in this article.

References

Altenhoff, W. J., Downes, D., Pauls., T., Schraml, J. 1979, AA Suppl, 35, 23
Bally, J., Stark, A.A., Wilson, R.W., Henkel, C. 1987, Ap.J. Suppl, 65, 13
Berkhuijsen, E.M., Beck, R., Gräve, R. 1987, in *Interstellar Magnetic Fields*, ed.

R.Beck and R.Gräve (Springer Verlag, Berlin), p.38
Brown, R.L, Liszt, H.S. 1984, ARAA, 22, 223
Downes, D., Goss, W.M., Schwarz, U.J., Wouterloot, J.G.A. 1978, AA Suppl, **35**, 1
Dulk, G.A., Slee, O.B. 1974, Nature, 248, 33
Duric, N., Seaquist, E.R., Crane, P.C., Bignell, R.C., Davis, L.E., 1983, Ap.J.L, 273, L11
Falcke, H., Mannheim, K., Biermann, P. L. 1993, AA, in press.
Fürst, E., Sofue, Y, Reich, W. 1987, AA, 191, 303
Genzel, R., Townes, C, H 1987, ARAA, 25, 377
Güsten, R. 1989, in *The Center of the Galaxy*, ed. M. Morris (Kluwer Academic Publishers, Dordrecht), p.89
Haslam, C.G.T., Salter, C.J., Stoffel, H., Wilson, W.E., 1982, AA Suppl, 47, 1
Haynes, R. F. ,, Stewart, R. T., Gray, A. D., Reich, W., Reich, P., Mebold, U. 1992, AA
Inoue, M., Takahashi, T., Tabara, H., Kato, T., Tsuboi, M. 1984, PASJ, 36, 633
Kaifu, N., Kato, T., Iguchi, T. 1972, Nature, 238, 105
Kapitzky, J.E., Dent, W.A. 1974, Ap.J., 188, 27
Krichbaum, T. P., Zensus, J. A., Witzel, A¿, Mezger, P. G., Standlke, K., et al. 1993, AA, 274, L37.
LaRosa, T.N., Kassim, N.E. 1985, Ap.J.L, 299, L13
Liszt, H.S. 1985, Ap.J.L, 293, L65
Little, A.G. 1974, in *Galactic Radio Astronomy, IAU Symp. No.60*, ed. F.J.Kerr and S.C.Simonson III (D.Reidel, Dordrecht), p.349
Lo, K.Y. 1986a, Science, 233, 1394
Lo, K.Y. 1986b, PASP, 98, 179
Mezger, P.G., Pauls, T. 1979, in *The Large-scale characteristics of the lGalaxy, IAU Symp. No.84*, ed. W.B.Burton (D.Reidel, Drodrecht), p.357
Mills, b.Y., Drinkwater, M.J. 1984, Austr.J.Phys., 5, 43
Morris, M. 1993, in this issue
Morris, M., Yusef-Zadeh, F. 1985, AJ, 90, 2511
Pauls, T., Downes, D., Mezger, P.G., Churchwell, W. 1976, AA, 46, 407
Predehl, P. 1993, in this issue.
Reich, W. 1993, in this issue
Reich, W., Fürst, E., Steffen, P., Reif, K., Haslam, C.G.T. 1984, AA Suppl, 58, 197
Reich, W., Reich, P., Füurst, E. 1990, AA Suppl.
Reich, W., Sofue, Y., Fürst, E. 1987, PASJ, 39, 573
Reich, W., Sofue, Y., Wielebinski, R., Seiradakis, J.H. 1988, 191, 303
Scoville, N.Z. 1972, ApJ.L., 175, L127
Seiradakis, J.H., Lasenby, A.N., Yusef-Zadeh, F., Wielebinski, R., Klein, U. 1985, Nature, 17, 697
Seiradakis, J.H., Reich, W., Wielebinski, R., Lasenby, A. N., Yusef-Zadeh, F. 1989, AA Suppl. 81, 291.
Serabyn, E., Güsten, R. 1986, AA, 161, 334
Serabyn, E., Lacy, J.H. 1985, Ap.J, 293, 445
Shibata, K., Uchida, Y. 1987, PASJ, 39, 559
Sofue, Y. 1984, PASJ, 36, 539

Sofue, Y. 1985, PASJ, 37, 697
Sofue, Y. 1989, Ap. Let. Commun., 28, 1.
Sofue, Y. 1990, PASJ, 42, 827.
Sofue, Y. 1989, in in *The Center of the Galaxy* (ed. M. Morris, Kluwer Academic Publishers, Dordrecht), p.213.
Sofue, Y. 1994, ApJ, March, in press.
Sofue, Y., Fujimoto, M. 1987, Ap.J.L, 319, L73
Sofue, Y., Fujimoto, M. 1987, PASJ, 39, 843.
Sofue, Y., Handa, T. 1984, Nature, 310, 568
Sofue, Y., Inoue, M., Handa, T., Tsuboi, M., Hirabayashi, H., Morimoto, M., Akabane, K. 1986, PASJ, 38, 483
Sofue, Y., Murata, Y., Reich, W. 1992, PASJ, 44, 367.
Sofue, Y., Reich, W., Inoue, M., Seiradakis, J.H. 1987, PASJ, 39, 359
Sofue, Y., Reich, W., Reich.P., 1988, Ap.J.L, 341, L47.
Tsuboi, M. 1993, in this issue
Tsuboi, M., Inoue, M., Handa, T., Tabara, H., Kato, T., Sofue, Y., Kaifu, N. 1986, AJ, 92, 818
Tsuboi, M., Handa, T., Inoue, M., Ukita, N., Takano, T. 1988, PASJ, 40, 665.
Uchida, K. I., Morris, M. R., Serabyn, E., and Bally, J. 1993, ApJ. in press.
Uchida, Y., Shibata, K. 1986, PASJ, 38,
Uchida, Y., Shibata, K., Sofue, Y. 1985, Nature, 317, 699
van Albada, R. D. 1980, AA Suppl. 39, 283.
Yusef-Zadeh, F. 1989, in *The Center of the Galaxy* (ed. M. Morris, Kluwer Academic Publishers, Dordrecht), p.243.
Yusef-Zadeh, F., Morris, M. 1986, Ph.D. Theis, Columbia University
Yusef-Zadeh, F., Morris, M. 1988, ApJ, 326, 574
Yusef-Zadeh, F., Morris, M., Chance, D. 1984, Nature, *Nature*, 310, 557
Yusef-Zadeh, F., Morris, M., Slee, O.B., Nelson, G.J. 1986, ApJ, 310, 689
Yusef-Zadeh, F., Morris, M., Slee, O.B., Nelson, G.J. 1986, ApJL, 300, L47

Figure Captions

Fig. 1: (a) 10 GHz continuum map of the Galactic center $3^\circ \times 2.5^\circ$ region. (b) 5 GHz VLA filaments of the radio Arc. Tick interval is $1'$. (Yusef-Zadeh 1986)

Fig. 2: (a) North Polar Spur at 408 MHz. $180^\circ \times 180^\circ$ area is shown. (background subtracted; from Haslam et al 1982).

(b) NGC 3079 at 1420 MHz (Duric et al 1983).

(c) NGC 4258 at 1420 MHz (van Albada 1982). Galactic planes are horizontal.