Radio Continuum and Molecular Gas in the Galactic Center

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Abstract

Nonthermal radio emission in the galactic center reveals a number of vertical structures across the galactic plane, which are attributed to poloidal magnetic field and/or energetic outflow. Thermal radio emission comprises star forming regions distributed in a thin, dense thermal gas disk. The thermal region is associated with dense molecular gas disk, in which the majority of gas is concentrated in a rotating molecular ring. Outflow structures like the radio lobe is associated with rotating molecular gas at high speed, consistent with a twisted magnetic cylinder driven by accretion of a rotating gas disk. [1]

1 Radio Continuum Emission

1.1 Flat Radio Spectra

The radio emission from the Galactic Center is a mixture of thermal and nonthermal emissions. The conventional method to investigate the emission mechanism is to study the spectral index, either flat (thermal) or steep (nonthermal). Howerver, the spectral index in the central 3° region has been found to be almost everywhere flat (Sofue 1985), even in regions where strong linear polarization has been detected. Therefore, a flat spectrum observed near the galactic center can no longer be taken as an indicator of thermal emission.

1.2 Infrared-to-Radio Intensity Ratio

Separation of thermal and nonthermal radio emission can be done by comparing far-IR (e.g. 60 μm) and radio intensities (both in Jy/str): thermal (HII) regions have high IR-to-radio ratio, $R = I_{\rm FIR}/I_{\rm R} \simeq 10^3$, while nonthermal regions have small IR-to-radio ratio, $R < 0 \sim 300$. Using this method, thermal and nonthermal emission regions have been distinguished in a wide area (Reich et al 1987). The region near the galactic plane is dominated by thermal emission and many

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HII regions like Sgr B2. These regions are closely associated with dense molecular clouds related to star formation in the clouds. On the other hand we find that many of the prominent features like the Radio Arc, Sgr A and regions high above the galactic plane including the Galactic Center lobe are nonthermal.

1.3 Linear Polarization

A direct and more convincing way to distinguish synchrotron radiation is to measure the linear polarization. However, extremely high Faraday rotation toward the Galactic Center causes depolarization due to finite-beam and finite-bandwidth effects. This difficulty has been resolved by developing 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). 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 in the GCL (Inoue et al 1984; (Tsuboi et al 1986; Seiradakis et al 1985; Sofue et al 1986; Reich 1988; Haynes et al 1992).

Linar polarization as high as $p \sim 50$ % has been detected along the Arc at mm wavelengths (Reich et al 1988). This is nearly equal to the theretical maximum, $p_{\mathrm{max}} = (\alpha+1)/(\alpha+7/3) \simeq 47$ %, for the Arc region, where the spectral index is $\alpha \simeq +0.2$. This implies that the magnetic field is almost perfectly alinged, consistent with the VLA observations showing straight filaments suggestive of highly ordered magnetic field (Yusef-Zadeh et al 1984; Morris 1993). From linear polarization it is clear that the radio emission from the radio Arc is nonthermal despite of its flat radio spectra.

2 Radio Continuum Morphology

2.1 Themral disk and Star Formation

The nuclear disk about 50 pc thick and 200 pc in radius comprises numerous clumps of HII regions, most of which are active star-forming (SF) regions, and are detected in the H recombination lines (Mezger and Pauls 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). However, if we take the GC distance of 8.5 kpc and a more accurate thermal/nonthermal separation, we estimate these to be $\sim 10^6 M_{\odot}$ and $1.5 \times 10^{52} \mathrm{s}^{-1}$, respectively. The SF rate of the central few hundred pc region amounts, therefore, to several % of the total SF rate of the Galaxy.

2.2 Thermal Filaments

Complex thermal filaments connect (bridge) Sgr A with the radio Arc (Yusef-Zadeh et al 1984). Recombination (Pauls et al 1976; Yusef-Zadeh et al 1986) and molecular line observations (Güsten 1989) indicate their thermal characteristics. However, large Faraday rotation is detected in the bridge, indicating co-existence of magnetic fields along the thermal filaments (Sofue et al 1987). Velocity dispersion of the thermal filamenets increases drastically near the Arc, indicative of violent interaction with the Arc (Pauls et al 1976). Yusef-Zadeh and Morris (1988) also argue that the

Arc (straight filaments) and the arched filaments are interacting. A magneto-ionic jet from Sgr A colliding the ambient poloidal magnetic field would explain this exotic structure (Sofue and Fujimoto 1987).

2.3 Radio Arc and Vertical Magnetic Fileds

The radio Arc comprises numerous straight filaments perpendicular to the galactic plane, and extends for more than $\sim$ 100 pc (Downes et al 1978; Yusef-Zadeh et al 1984; Morris 1993) The magnetic field direction is parallel to the filaments and vertical to the galactic plane (Tsuboi et al 1986). Field strength as high as $\sim$ 1 mG has been estimated in the Arc and in some filaments (Morris 1993). The life time of cosmic-ray electrons in the Arc is estimated to be as short as $\sim$ 4000 years (Sofue et al. 1992), and so the straight filaments may be transient features, temporary illuminated by recently accelerated high-energy electrons.

The higher latitude extension of the Arc, both toward positive and negative latitudes, is also polarized by 10 to 20% (Tsuboi et al 1986; Sofue et al 1987). The rotation measure reverses across the galactic plane, indicating a reversal of the line-of-sight component of the magnetic field. This is consistent with a large-scale poloidal magnetic field twisted by the disk rotation (Uchida et al 1985).

2.4 Galactic Center Lobe and Large-scale Ejection

The Galactic Center lobe (GCL) is a two-horned vertical structure, probably a cylinder of about 200 pc in diameter (Sofue and Handa 1984; Sofue 1985: Fig. 1). The eastern ridge of the lobe is an extension from the radio Arc, and is strongly polarized. The western ridge emerges from Sgr C. An MHD acceleration model in which the gas is accelerated by a twist of poloidal magnetic field by an accreting gas disk has been proposed (Uchida et al 1985; Uchida and Shibata 1986). High-velocity molecular gas has been found to be associated with the GCL (Sofue 1996: Fig. 1): Molecular gas in the eastern GCL ridge is receding at $V_{\rm lsr} \sim +100$ km s^{-1}, and the western gas is approaching at ~ -150 km s^{-1}, indicating rotation of the GCL. This is consistent with the twisted magnetic cylinder model.

A much larger scale ejection has been found in radio, which emanates toward the halo, reaching as high as $b \sim 25°$ (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 it might be magnetic tornado produced by the differential rotation between the halo and the nuclear disk.

2.5 Huge Galactic Bubble by Starburst: North Polar Spur

The radio North Polar Spur traces a giant loop on the sky of diamter about 120°, drawing a huge Ω over the galactic center (Fig. 2). The Ω-shape can be simulated by a shock front due to an explosion (sudden energy input) at the galactic center (Sofue 1994). In this model, the distance to NPS is several kpc. The X-ray intensity variation as a function of latitude indicates that the source is more distant than a few kpc, beyond the HI gas disk, consistent with the Galactic Center explosion model, but inconsistent with the local supernova remnant hypothesis.

Figure 1: 10 GHz radio map of the Galactic center $2.2^\circ \times 3^\circ$ (left bottom), in comparison with a $l - V_{\rm lsr}$ plot of the ^{13}CO emission at $b = 8'$ (top). showing high-velocity rotating gas in the GCL. A VLA map (right) at 5 GHz shows vertical magnetic field filaments in the Arc (tick mark interval is $1'$; Yusef-Zadeh 1986).

Figure 2: North Polar Spur at 408 MHz after background subtraction (Haslam et al1982; Sofue 1994). A shock wave associated with a starburst of total energy release of 10^{55} ergs is shown at 10, 15 and 20 million years. The front at 15 million years can fit the radio shell.

Figure 3: ^{13}CO intensity map (Bally et al 1987; Sofue 1995), showing a highly-tilted ring structure of the molecular gas (bottom), in comparison with an (l, V) diagram at $b = 2'$ and $-5'$ (top). Arm I and II correspond to the upper and lower parts of the tilted ring.

Hence, the NPS is naturally explained, if the Galaxy experienced an active phase 15 million years ago associated with an explosive energy release of some 10^{56} erg (Sofue 1994). This suggests that a starburst had occurred in our Galactic Center, which involved $\sim 10^5$ supernovae during a relatively short period (e.g., 10^6 yrs).

3 Molecular Arms and 120-pc Ring

Various molecular features have been recoginzed in the central $\sim 100 - 200$ pc region: such as molecular rings and arms of a few hundred pc scale (Scoville et al.1974; Heiligman 1987), shell structures and complexes around HII regions (e.g., Hasegawa et al 1993), and an expanding molecular ring of 200 pc radius (Scoville 1972; Kaifu et al.1972). Binney et al. (1991) have noticed a "parallelogram" instead of an expanding ring, and interpreted it in terms of non-circular kinematics of gas by in an oval potential. However, the gas in this parallelogram shares only a minor fraction of the total gas mass (~ 10 %).

Fig. 3 shows the total intensity map integrated over the full range of the velocity (Bally et al 1987; Sofue 1995). The total molecular mass in the $|l| < 1°$ region is estimated to be $\sim 4.6 \times 10^7 M_\odot$ for a new conversion factor (Arimoto et al 1995). The molecular mass of the "disk" component is $\sim 3.9 \times 10^7 M_\odot$, which is 85% of the total in the observed region. The expanding ring (or the parallelogram) shares the rest, only $7 \times 10^6 M_\odot$ (15%) in the region.

Figure 4: Possible deconvolution of the CO (l, V) diagrams for Galactic Center into a face-on view.

The HI mass within the central 1 kpc is only of several $10^6 M_{\odot}$ (Liszt & Burton 1980). Hence, the central region is dominated by a molecular disk of ~ 150 pc ($\sim 1°$) radius, outside of which the gas density becomes an order of magnitude smaller. The total gas mass within 150 pc is only a few percent of the dynamical mass ($M_{\rm dyn} = RV_{\rm rot}^2/G \sim 8 \times 10^8 M_{\odot}$ for a radius $R \sim 150$ pc and rotation velocity $V_{\rm rot} \sim 150$ km s^{-1}. This implies that the self-gravity of gas is not essential in the galactic center.

Fig. 3 shows (l, V) diagrams in the galactic plane, where the foreground components have been subtracted (Sofue 1995). The major structures of the "disk component" near the galactic plane are "rigid-rotation" ridges, which we call "arms". The most prominent arm is found as a long and straight ridge, slightly above the galactic plane at $b \sim 2'$, marked as Arm I in the figure. Its positive longitude part is connected to the dense molecular complex Sgr B. Another prominent arm is seen at negative latitude at $b \sim -6'$, marked as Arm II.

Arms I and II compose a bent ring of radius 120 pc with an inclination 85°. We call this ring the 120-pc Molecular Ring. It is possible to deconvolve the (l, V) diagram into a spatial distribution in the galactic plane by assuming approximately circular rotation and using the velocity-to-space transformation (VST). Fig. 4 shows a thus-obtained possible "face-on" map of the molecular gas for $V_0 = 150$ km s^{-1}. HII regions are also plotted, showing that HII regions lie along the molecular complexes along the arms in the ring.

4 Discussion

We have reviewed various features in the central 150 pc region of the Galaxy in radio continuum, both in thermal and nonthermal, and in the CO line. The thermal radio emission and molecular gas are distributed within a thin disk of 150 pc radius and 30 pc thickness. The nonthermal radio emission is distributed in a wider area, often extending far from the galactic plane, comprising vertical structures associated with poloidal magnetic fields.

We estimate some energetics among the variuos ISM in the central 150 pc region: Molecular gas has turbulent energy density of a few 10^{-8} erg cm^{-3}, when averaged in the central 150 pc radius disk. Energy densities due to HII gas and Ly continuum photon are of the order of $\sim 10^{-10}$ erg cm^{-3}. On the other hand, the magnetic field energy is as high as $\sim 4\times10^{-8}$ erg cm^{-3} for ∼mG field strength. The molecular gas disk and magnetic field appear to be in an energy balance with each other, with the magnetic energy dominating. The averaged star formation rate compared to the molecular gas amount, or the SF efficiency, is much lower than that observed in the outer disk of the Galaxy. If the Galaxy had experienced a starburst 15 million years ago such as that suggested for the cause of the hugh NPS shell, the present Galactic Center may be in a quiet phase, probably in a pumping-up phase for the next burst.

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