PART II.

NUCLEAR INTERSTELLAR MEDIUM

4. Neutral ISM in the Galactic Center

RADIO CONTINUUM AND MOLECULAR GAS IN THE GALACTIC CENTER: LARGE-SCALE STRUCTURES

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1. Radio Continuum Emission: Thermal/Non-thermal Decomposition

The radio emission from the Galactic Center is a mixture of thermal (free-free) and non-thermal (synchrotron) emissions (Fig. 1a). However, the spectral index in the central 3° region is flat almost everywhere (Sofue 1985), even in regions where strong linear polarization is detected. Therefore, a flat spectrum observed near the galactic center can no longer be taken as an indicator of thermal emission.

Separation of thermal and non-thermal emissions can be done by comparing far-IR (e.g. 60 μm) and radio intensities (in Jy/str): thermal (HII) regions have high IR-to-radio ratio, $R = I_{\rm FIR}/I_{\rm R} \simeq 10^3$, while non-thermal regions have small ratio, $0 \sim 300$. Using this method, thermal and non-thermal emission regions have been distinguished in a wide area (Reich et al 1987). The region near the galactic plane ($b <\sim 10'$) is dominated by thermal emission, mostly HII regions like Sgr B2 and C. These regions are closely associated with dense molecular clouds. On the other hand, the prominent features like the Radio Arc, Sgr A and regions high above the galactic plane including the Galactic Center lobe have small IR/radio ratio, corresponding to their non-thermal nature.

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 de-polarization due to finite-beam and finite-bandwidth effects. This difficulty has been resolved by developing a multi-frequency narrow-band Faraday polarimeter (Tsuboi et al 1986; Seiradakis et al 1985; Sofue et al 1987; Reich 1994; Haynes et al 1992), as well as by high-resolution and high-frequency observations using the VLA

Y. Sofue (ed.), The Central Regions of the Galaxy and Galaxies, 161-168.

(Yusef-Zadeh et al 1984, 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.

Linear polarization as high as $p \sim 50$ % has been detected along the Arc at mm wavelengths (Reich 1994). This is nearly equal to the theoretical maximum, $p_{\max} = (\alpha + 1)/(\alpha + 7/3) \simeq 47$ %, for the Arc region, where the spectral index is $\alpha \simeq +0.2$. This implies that the magnetic field is almost perfectly aligned, consistent with the VLA observations showing straight filaments suggestive of highly ordered magnetic field (Yusef-Zadeh et al 1984; Morris 1997).

2. Thermal Structure

2.1. STAR-FORMATION DISK

The nuclear disk ~ 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 B2, 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 1.5×10^{52} 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. The averaged star formation rate compared to the molecular gas (SF efficiency) is not particularly high compared to that observed in the outer disk of the Galaxy. Namely, the galactic center is not in an active phase of star formation, and therefore, not a starburst. However, evidence is present for a past starburst some 10^7 yrs ago (see section 3).

2.2. RADIO VS MOLECULAR STRUCTURES

Various molecular features have been recognized in the central ~ 100 – 200 pc region: such as molecular rings and arms of a few hundred pc scale (Scoville et al.1974), shell structures and complexes around HII regions (Hasegawa 1997), and an expanding molecular ring of 200 pc radius (Scoville 1972; Kaifu et al.1972, Sofue 1995b). Binney et al. (1991) have noticed a "parallelogram" instead of an expanding ring, and interpreted it in terms of non-circular kinematics of gas in an oval potential. However, we emphasize that the gas in this parallelogram shares only a minor fraction (~ 10 %) of the total gas mass, and is distributed high (~ ±20 – 30 pc) above the major molecular disk.

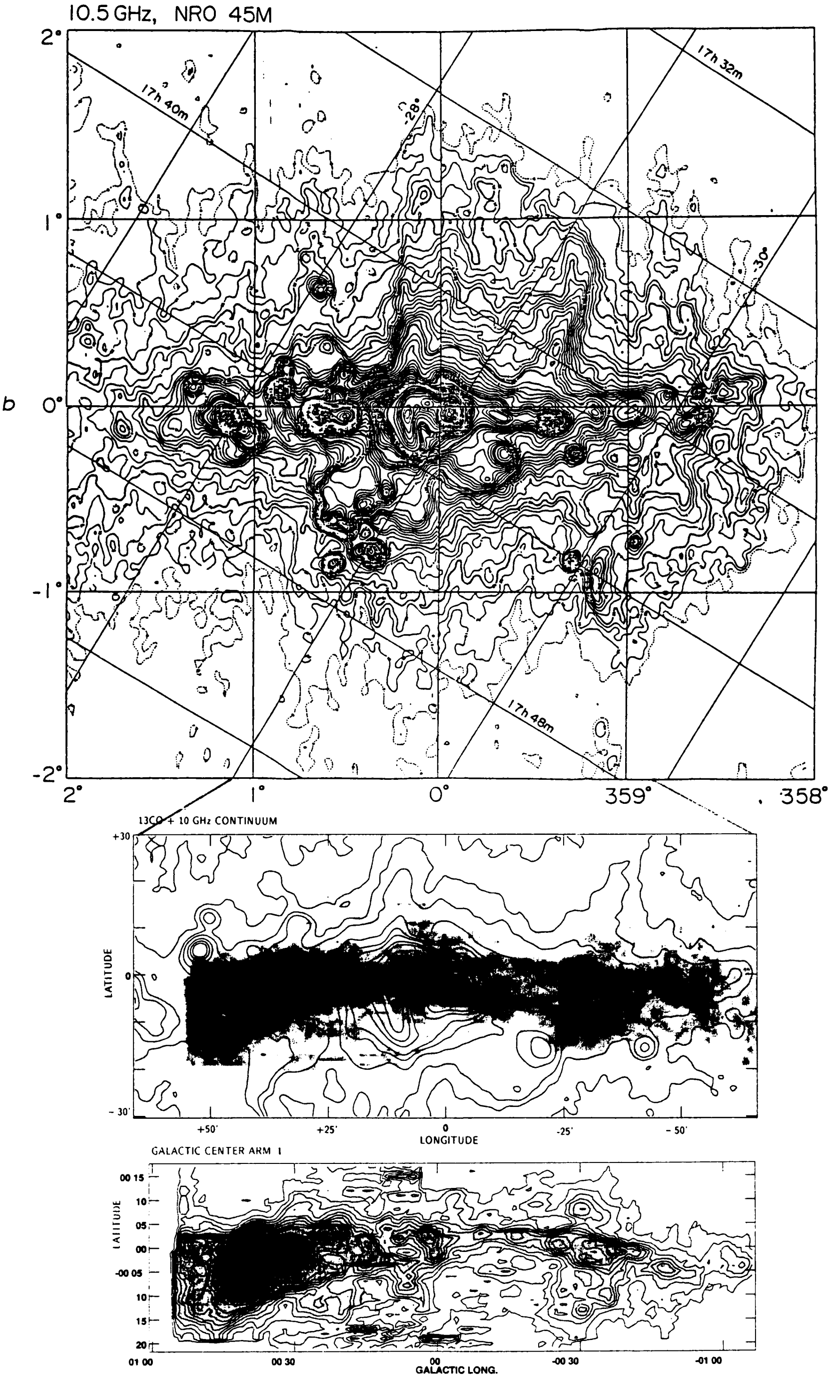

Figure 1. (a) 10 GHz radio map of the Galactic center. (b) Highly-tilted molecular ring (Bally et al 1987; Sofue 1995a) superposed on radio continuum contours. (c) Molecular Arm I.

Fig. 1b shows the total intensity map integrated over the full range of the velocity (Bally et al 1987), where the foreground components have been subtracted (Sofue 1995a). The total molecular mass in the $|l| < 1^\circ$ region is estimated to be $\sim 4.6 \times 10^7 M_\odot$ for the new conversion factor which takes into account the increase in metallicity toward the galactic center (Arimoto et al 1995). The molecular mass of the disk (ring) component is $\sim 3.9 \times 10^7 M_\odot$, which is 85% of the total molecular mass in the observed region. The expanding ring (or the parallelogram) shares the rest, only $7 \times 10^6 M_\odot$ (15%) in the region. The HI mass within the central 1 kpc is small, $\sim 10^6 M_\odot$ (Liszt & Burton 1980). Hence, the central region is dominated by a molecular disk of ~ 150 pc ($\sim 1^\circ$) 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 ($\sim 8 \times 10^8 M_\odot$) for a radius $R \sim 150$ pc. This implies that the self-gravity of gas is not essential in the galactic center.

Longitude-position diagram of the CO line emission shows that the major structures of the disk (ring) component near the galactic plane lie on rigid-rotation-like ridges, which comprises two major arms: The most prominent arm is Arm I, which is a long and straight ridge, slightly above the galactic plane at $b \sim 2'$ (Fig. 1c). Its positive longitude part is connected to the dense molecular complex Sgr B. Another prominent arm is seen at negative latitude at $b \sim -6'$ (Arm II).

2.3. CIRCULAR ROTATION

Arms I and II compose a bent ring of radius 120 pc with an inclination 85° (Fig. 1b: Sofue 1995a), which we call the 120-pc Molecular Ring. The molecular ring structure has already been known since two decades ago (Scoville et al 1974). 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. 2 shows a thus-obtained possible "face-on" map of the molecular gas. HII regions (Sgr B and C) lie close to the molecular complexes along the arms in the ring.

The close association of the SF regions with the molecular clouds, from which the stars were born, indicates that the stars and gas are moving along nearly the same orbit. This can be realized only when the molecular gas is rotating in a circular orbit in an axi-symmetric potential: If the potential was oval (bar) and the gas was shocked to be compressed along a bar, the formed stars)would have displaced from the gaseous arms since the birth $t \sim 10^7$ yrs ago, and their angular separation would have increased to $\Delta\Omega = \Omega_{\rm rot} - \Omega_{\rm pattern} \sim 75^\circ$. However, this contradicts the observation,

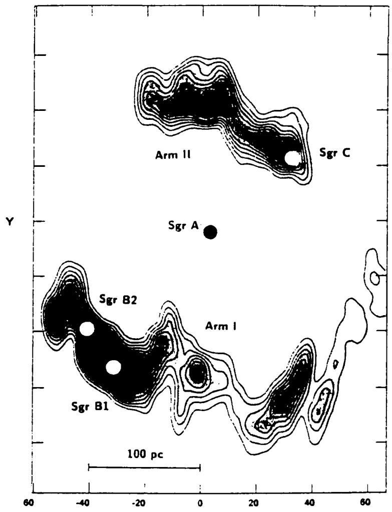

Figure 2. A decomposed face-on view of the molecular ring. HII regions are marked by white circles.

which indicates $\Delta\Omega < 5°$.

3. Nonthermal Structures

3.1. VERTICAL MAGNETIC FIELDS VS CIRCULAR RING

The radio Arc comprises numerous straight filaments perpendicular to the galactic plane, and extends for more than $\sim$ 100 pc (Yusef-Zadeh et al 1984; Morris and Yusef-Zadeh 1985; Morris 1997) The magnetic field direction is parallel to the filaments and vertical to the galactic plane (Tsuboi et al 1986; Sofue et al 1987; Reich 1994). Field strength as high as $\sim$ 1 mG has been estimated in the Arc and in some filaments. The life time of cosmic-ray electrons in the Arc is estimated to be as short as $\sim$ 4000 years, so that the straight filaments may be transient features, temporary illuminated by recently accelerated high-energy electrons (Sofue et al. 1992).

The higher latitude extension of the Arc, both toward positive and negative latitudes, is also polarized by 20 to 50% (Tsuboi et al 1986; Sofue et al 1987; Reich 1994). 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).

Molecular gas has turbulent energy density of $u_{\rm mol.tur.} \sim 6 \times 10^{-9}$ erg cm^{-3} for a velocity dispersion of 20 km s^{-1}, when averaged in the central 150 pc radius disk. Energy densities due to HII gas and Ly continuum photon are of the order of $u_{\rm HII,LyPho} \sim 10^{-10}$ erg cm^{-3}, manifesting the weak star-forming activity. The magnetic energy density is of the order of $\sim 4 \times 10^{-8}$ erg cm^{-3} for ~mG field strength. This amount is more comparable to the rotation energy of the molecular disk, which corresponds to an energy density of $u_{\rm rot} \sim 3 \times 10^{-7}$ erg cm^{-3}. The magnetic energy exceeds the turbulent energy of gas, but is smaller than the rotation energy.

The un-balanced energetics is more prominent in the vertical features: The vertical magnetic fields such as the arc and high-latitude polarized features are located at radius of $r < 40$ pc, where only a very little amount of ISM is observed. Except for some clumpy molecular features, the vertical magnetic features are not associated with any particular gaseous structures, which is dense and massive enough to anchor the field. On the other hand, the molecular gas is distributed in a circular ring at $r \sim 120$ pc, where no particularly strong vertical field is observed. Not only in the appearance and location but also in energetics, the vertical fields and the molecular disk appear to exist separately.

3.2. GAS DYNAMICS, MAGNETISM, AND ANGULAR MOMENTUM

The dynamics of ISM will be strongly affected by the presence of magnetic field, particularly in the central few tens of pc region (inside the ring). There have been extensive simulations of gas dynamics in the center (e.g., Combes 1997; Noguchi 1997; Wada 1997), in which, however, the magnetism has been neglected. Moreover, the magneto-hydrodynamics is essentially three-dimensional, and the behavior of the gas dynamics, such as accretion toward the nucleus, would be three-dimensional. In this context, MHD simulations of jets and vertical flows, which combines accretion and twisted field (Shibata and Uchida 1987, could be unified with the self-gravitating bar-accretion simulations.

The origin of the vertical field will be the remnant of the vertical component of primordial large-scale galactic field, which has been accumulated to the center during the accretion of gaseous disk (Sofue and Fujimoto 1987). If this is the case, the vertical field is connected to the intergalactic magnetic field outside the halo, and, therefore, its force-free state is of non-rotating. This implies that the central vertical field can be a large-capacity reservoir of angular momentum of accreting gas, which makes the accretion more efficient even in a circular rotation.

3.3. LARGE-SCALE EJECTION AND LOPSIDEDNESS

The Galactic Center lobe (GCL) is a two-horned vertical structure, likely 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, while the western ridge emerges from Sgr C. An

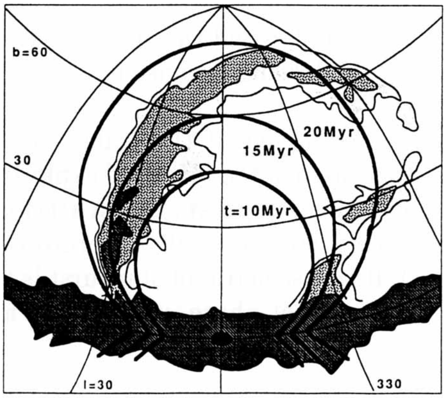

FIG. 2a

Figure 3. The North Polar Spur can be fitted by a shock wave due to a starburst 15 million years ago.

MHD acceleration model has been proposed, in which the gas is accelerated by a twist of poloidal magnetic field by an accreting gas disk (Uchida et al 1985). 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. This jet-like features appears to be associated with the recently discovered plume of the 0.5 MeV positron annihilation γ-rays (Purcell et al. 1997). It is interesting to point out that the large-scale ejection features (GCL, 4-kpc jet, the North Polar Spur, the γ-ray anti-matter plume) are all one-sided toward the north.

3.4. STARBURST 1.5×10^7 YEARS AGO AND ITS REMNANT IN THE HALO

The radio North Polar Spur (e.g. Haslam et al 1982) traces a giant loop on the sky with a diameter of 120°, drawing a huge Ω over the galactic center, again lopsided in the northern halo (Fig. 3). 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.

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 ($\sim 10^6$ yrs). If this scenario of starburst is the case, the present Galactic Center may be in a quiet phase, probably in a pumping-up phase for a coming burst.

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