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Evidence of a Weak Galactic Center Magnetic Field from Diffuse Low-Frequency Nonthermal Radio Emission

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EVIDENCE OF A WEAK GALACTIC CENTER MAGNETIC FIELD FROM DIFFUSE LOW-FREQUENCY NONTHERMAL RADIO EMISSION

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ABSTRACT

New low-frequency 74 and 330 MHz observations of the Galactic center (GC) region reveal the presence of a large-scale (6° × 2°) diffuse source of nonthermal synchrotron emission. A minimum-energy analysis of this emission yields a total energy of $\sim(\phi^{4/7} f^{3/7}) \times 10^{52}$ ergs and a magnetic field strength of $\sim 6(\phi/f)^{2/7}$ μG (where ϕ is the proton to electron energy ratio and f is the filling factor of the synchrotron emitting gas). The equipartition particle energy density is $1.2(\phi/f)^{2/7}$ eV cm^{-3}, a value consistent with cosmic-ray data. However, the derived magnetic field is several orders of magnitude below the 1 mG field commonly invoked for the GC. With this field the source can be maintained with the supernova rate inferred from the GC star formation. Furthermore, a strong magnetic field implies an abnormally low GC cosmic-ray energy density. We conclude that the mean magnetic field in the GC region must be weak, of order 10 μG (at least on size scales ≳125″).

Subject headings: Galaxy: center — ISM: magnetic fields — radio continuum: ISM

1. INTRODUCTION

An outstanding question in Galactic center (GC) studies concerns the origin, strength, and role of magnetic fields in the region. Large-scale filamentary nonthermal structures (two dozen confirmed), with lengths of up to tens of parsecs, have been observed in the vicinity of the GC for over the last two decades (e.g., Morris & Serabyn 1996 and references therein; Lang et al. 1999; LaRosa et al. 2001, 2004; Nord et al. 2004; Yusef-Zadeh et al. 2004). The spatial distribution of the nonthermal filaments (NTFs) is confined to within ~1°.5 of the GC, and this phenomenon seems to be unique to the GC region. The NTFs are widely believed to be magnetic field lines illuminated by the injection of relativistic particles. Within the context of this picture, it has been suggested that a pervasive, strong (~1 mG) magnetic field must permeate the entire GC region in order to confine the NTFs (see, e.g., Morris & Serabyn 1996 and references therein). This Letter reports the discovery of a previously unrecognized diffuse, nonthermal structure in the GC and shows that its properties are not consistent with a strong, space-filling magnetic field.

2. OBSERVATIONS AND RESULTS

We have used the Very Large Array[6] (VLA) in all four configurations to image the Galactic center region at 74 MHz. The resulting image presented in Figure 1*a* has a resolution of 125″, an rms noise of ~0.2 Jy beam^{-1}, and a dynamic range of ~200. The details of the 74 MHz data reduction are discussed more thoroughly in Brogan et al. (2003; C. L. Brogan et al. 2005, in preparation). This is the highest resolution and sensitivity image of the Galactic center region at frequencies below 300 MHz yet created. Even so, the data used to make Figure 1*a* were tapered to provide surface brightness sensitivity optimized to the large-scale emission which is the focus of this Letter. Future improvements in ionospheric calibration offer the opportunity to achieve the full resolving power of the VLA at 74 MHz and to produce a map more suited to studying smaller, discrete sources.

A wide range of discrete emission and thermal absorption features are evident in the 74 MHz image (Brogan et al. 2003; C. L. Brogan et al. 2005, in preparation), as well as a large-scale region of diffuse emission surrounding Sgr A and extending $l \pm 3°$ in longitude and $b \pm 1°$ in latitude. At a distance of 8 kpc this angular scale corresponds to a region 840 × 280 pc. Interestingly, none of the NTFs are detected in the 74 MHz image, and away from known supernova remnants, the emission is quite smooth. The extent of the large-scale low-frequency structure is well matched in size to that of the central molecular zone (CMZ); the region surrounding the Galactic center where the molecular gas density, temperature, and velocity dispersion are high (see Brogan et al. 2003; Morris & Serabyn 1996). We hereafter refer to the low-frequency structure as the Galactic center diffuse nonthermal source (DNS). The even larger scale, smooth Galactic background is resolved out of this image due to the spatial filtering afforded by the interferometer; only structures smaller than ~5°.5 (the angular scale corresponding to the shortest baseline) down to the resolution limit of 125″ are sampled. Although the size of the DNS is comparable to the largest angular scale to which our measurements are sensitive, two of its characteristics strengthen our confidence that it is a distinct source: (1) the strong thermal absorption in the vicinity of the GC itself (Fig. 1*a*) effectively segregates the DNS into two pieces, each of which is considerably smaller than 5°.5, and (2) the DNS is also detected in higher frequency (330 MHz) single-dish data (see below).

To complement our 74 MHz data, we have imaged a 15° × 15° region centered on the GC with the Green Bank Telescope (GBT) at 330 MHz. The GBT data were obtained with a 20 MHz bandwidth, 1024 spectral channels, and a scanning rate that more than Nyquist sampled the beam (38′.9). The GC region is bright enough at 330 MHz that attenuators are required to avoid saturating the detectors. The effect of this high attenuation setting was carefully calibrated out of the flux calibration scans on 3C 286 and the observations of the off-positions. In order to

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correct for the nonzero temperature of the off-positions located at $(l, b) = (\pm 20°, 0°)$, estimates for the sky brightness at these two locations were estimated from the 408 MHz survey image (Haslam et al. 1982) assuming a spectral index of −2.7 (Platania et al. 2003) and added back to the 330 MHz image. Finally, the image was converted to a flux density scale using the observed antenna temperature of 3C 286 compared to its expected brightness temperature (Ott et al. 1994) and the gain of the GBT (approximately 2 K Jy^{-1} at low frequencies).

A subimage of the resulting GBT 330 MHz image with a resolution of 38′.9 is shown in Figure 1*b*. This image includes contributions from all of the discrete sources apparent in the high-resolution VLA 330 MHz image by LaRosa et al. (2000), the DNS, and the smooth Galactic background synchrotron emission, with the latter contributing much of the total flux. Thus, the Galactic background must be removed and the discrete source contribution accounted for before the 330 MHz properties of the DNS can be assessed. For background subtraction we chose a constant longitude slice free of discrete sources (and well outside of the DNS) near $l = 354°.5$ and subtracted it from every other constant longitude plane (median weight filtering was not used since it can introduce structures on size scales equal to the filter). The image resulting from this procedure is shown in Figure 1*c*. Despite the resolution difference, there is excellent agreement between the diffuse structure visible in the background-subtracted GBT 330 MHz image (Fig. 1*c*) and the 74 MHz VLA image (Fig. 1*a*).

Having established the reality of the DNS, we now estimate its integrated 74 and 330 MHz flux and spectral index. Due to the copious thermal absorption at 74 MHz apparent in Figure 1*a*, a simple integration of the total flux within the DNS region is impossible. Instead, we have used the average 74 MHz flux density at locations within the DNS that appear free of both discrete emission sources and thermal absorption, together with its apparent size (an ellipse of dimension 6° × 2°) to calculate its total flux. Using this method we find an integrated 74 MHz flux density for the DNS of 16.2 ± 1 kJy. This estimate is likely to be a lower limit, however, as we show below an underestimate of the total 74 MHz flux density of the DNS does not significantly affect our arguments regarding the weakness of the large-scale GC magnetic field.

The integrated 330 MHz flux density within the boundaries of the DNS (Fig. 1*c*) is ∼8000 Jy, while the total flux density contained in discrete sources from the VLA 330 MHz image (LaRosa et al. 2000) is ∼1000 Jy.[7] Thus, we estimate that the integrated 330 MHz flux density of the DNS is ∼7000 Jy. Except for the immediate vicinity of the Galactic center itself (where the *thermal* ionized gas density is very high), thermal absorption effects should not be a significant effect at 330 MHz (see, e.g., Nord et al. 2004) Combined with the lower limit to the 74 MHz DNS flux, we find that the spectral index of the DNS must be steeper than −0.7 (assuming $S_\nu \propto \nu^\alpha$) or −2.7 if brightness temperatures are considered. This value is comparable to the brightness temperature spectral indices measured for the Galactic plane synchrotron background emission (−2.55 to −2.7; see Platania et al. 2003).

2.1. *Minimum-Energy Analysis*

Using standard synchrotron theory (Moffat 1975), the minimum energy and magnetic field are given by $U_{\min} = 0.5(\phi AL)^{4/7}V^{3/7}$ and $B(U_{\min}) = 2.3(\phi AL/V)^{2/7}$. Here A is a function of the spectral index, L is the luminosity, V is the source volume, and ϕ is the ratio of energy in protons compared to electrons. Using a 74/330 MHz spectral index of −0.7 and integrating from 10 MHz to 100 GHz, we find a total luminosity for the DNS of 3×10^{36} ergs s^{-1} (we have used $S_{330} =$ 7000 Jy and $S_\nu = S_{330}\nu^{-0.7}$ for this calculation). If, for example, the spectral index were actually as steep as −1.5, the luminosity would still be $>10^{36}$ ergs s^{-1}. Thus, the possibility that we have underestimated the 74 MHz flux is unlikely to significantly impact this analysis. Assuming that the depth of the DNS is 480 pc (the geometric mean diameter assuming a distance of 8 kpc), the minimum energy is $(\phi^{4/7}f^{3/7}) \times 10^{52}$ ergs and the corresponding magnetic field strength is $6(\phi/f)^{2/7}$ μG, where f is the filling factor of the nonthermal emission within the volume V. With these values, the equipartition particle energy density is $1.2(\phi/f)^{2/7}$ eV cm^{-3}. A filling factor as low as 1% will only increase the derived field strength and particle density by a factor of ∼4. A large proton to electron energy ratio of 100 could increase these estimates by another factor of ∼4. Thus, even with these extreme parameters, the magnetic field on size scales larger than the 74 MHz beam (125″) must be ≲100 μG.

The above calculation applies to the entire 6° × 2° region spanned by the DNS. However, the nonthermal filaments are found only in the inner 1°.5 × 0°.5. The integrated 330 MHz flux in this smaller region is ∼1000 Jy and yields a minimum energy of $(\phi^{4/7}f^{3/7}) \times 10^{51}$ ergs (electron energy density of ∼7.2 eV cm^{-3}) and magnetic field of $11(\phi/f)^{2/7}$ μG. Thus, the gradient in the DNS brightness does not translate into a significantly larger magnetic field in the innermost region compared to the region as a whole.

3. DISCUSSION

3.1. *Energy Requirements*

For the minimum-energy parameters the radiative lifetime of electrons generating the DNS is of order 5×10^7 yr while a strong 1 mG magnetic field would have a much shorter synchrotron lifetime, only 10^5 yr. The energy contained in a typical supernova remnant in particles and the magnetic field is 5×10^{49} ergs (Duric et al. 1995), so that ∼200 supernovae (SNe) within the last 5×10^7 yr are required to power the DNS. The SN rate scales with the star formation rate, which is a factor of ≈250 higher in the inner 50 pc than in the disk (Figer et al. 2004). Given this enhanced star formation rate, the GC SN rate of about *one* per 10^5 yr is sufficient to power the DNS and maintain its equilibrium. Alternatively, the DNS could be due to a single extreme event (with an energy of ∼10^{52} ergs) or was formed during a *recent* starburst. Indeed, the presence of a large bipolar wind structure centered on the GC from dust and radio emission studies suggests that our GC has undergone periods of more prolific star formation in the past (e.g., Sofue & Handa 1984; Bland-Hawthorn & Cohen 2003). However, Bland-Hawthorn & Cohen (2003) estimate that the GC "Omega lobe" was formed during a starburst event 10^7 yr ago, inconsistent with the 1 mG synchrotron lifetime. Additionally, the agreement between the derived DNS spectral index (−0.7) and that of the diffuse Galactic plane emission suggests that the acceleration mechanism is similar. This steep spectral index also suggests that the emission arises from a relatively old population of electrons.

In contrast, the synchrotron lifetime in a 10 μG field is 10^8 yr. With this longer lifetime, the ∼200 SNe required to power the DNS are entirely consistent with the enhanced GC SN rate (10^5 yr per SN). This scenario for the generation of the DNS is also consistent with the diffuse soft X-ray emission from the GC

[7] The VLA 330 MHz image is not sensitive to structures larger than ∼1° and thus contains little or no contribution from the Galactic background or the DNS.

region. Muno et al. (2004) report the presence of diffuse hard ($kT \sim 8$ keV) and soft ($kT \sim 0.8$ keV) X-ray emission from the inner 20 pc. The soft component requires input of the energy equivalent of one SN every 10^5 yr, in good agreement with the rate required to explain the DNS. The hard component is more difficult to explain with this injection rate (requiring ∼1 SN per 3000 yr), but Muno et al. suggest that a significant fraction of the hard emission may arise from unresolved cataclysmic variables and other compact objects, so that the high implied rate may be overestimated.

3.2. *Constraints on GC Cosmic-Ray Energy Density*

By construction, the minimum-energy procedure constrains the field and particle energies together but they can also be analyzed separately. Consider the inner $1\overset{\circ}{.}5 \times 0\overset{\circ}{.}5$ where the magnetic field is often assumed to be 1 mG. The integrated flux of the DNS in this region is ∼1000 Jy. Assuming a 1 mG magnetic field, this flux requires a cosmic-ray (CR) electron energy density of 0.04 eV cm^{-3}. In contrast, the energy density of electrons in the local interstellar medium (ISM) is a factor of 5 larger (0.2 eV cm^{-3}; Webber 1998). Thus, unless the electron energy density in the GC region is significantly lower than that in other parts of the Galaxy, a 1 mG field is inconsistent with the 330 MHz data.

The cosmic-ray energy density in a particular region is determined by the local balance between CR production and escape rates. In the disk, particles escape with a typical turbulent diffusion velocity of order 10–15 km s^{-1} (e.g., Wentzel 1974). In contrast, it is likely that particles in the GC region escape much more rapidly due to strong winds of order a few thousand kilometers per second (see, e.g., Suchkov et al. 1993 and Koyama et al. 1996). However, since the production rate scales with the SN rate, which exceeds that of the disk by a factor of ∼250 in the GC region, the higher escape rate in the GC could be balanced by the higher production rate. Thus, the cosmic-ray energy density in the Galactic center region may well be similar to that measured in the disk. Unfortunately, no direct *measurements* of the GC cosmic-ray energy density currently exist. There are, however, a number of indirect indicators that can be used to constrain its properties.

Diffuse γ-ray emission in our Galaxy is produced by the interaction of high-energy cosmic rays with interstellar material, as well as a relatively uncertain contribution from unresolved compact sources (e.g., pulsars, X-ray binaries, etc.). Thus, γ-ray emission can be expected to peak where the cosmic-ray density is high, the gas density is high, or there is a high concentration of compact objects. Recent reanalysis of all available EGRET data toward the GC region by Mayer-Hasslewander et al. (1998) suggest a number of pertinent conclusions: (1) the level of γ-ray emission within the DNS region is entirely consistent with that predicted by models of the Galactic disk (Hunter et al. 1997) with the exception of a $\lesssim 0\overset{\circ}{.}6$ radius region of enhanced emission centered on the GC itself. (2) Taking into account newer estimates of the GC gas mass, this finding disputes earlier claims that there is a *deficit* of cosmic rays toward the GC region (e.g., Blitz 1985). (3) No excess is observed toward the Sgr B, Sgr C, or Sgr D molecular cloud complexes as might be expected if gas density played a large role in the GC γ-ray emissivity. (4) The spectrum of the *excess* GC γ-ray emission is significantly harder than that of the Galactic disk and most likely arises from the GC radio arc and/or compact objects like pulsars.

Galactic center molecular clouds have significantly higher temperatures, densities, and turbulent velocities than their disk counterparts (i.e., the CMZ; Morris & Serabyn 1996; Rodríguez-Fernández et al. 2004). In the past, heating by a larger than average CR energy flux has been invoked to explain the high temperatures of the GC clouds (Suchkov et al. 1993). More recently, a number of studies have shown that the required heating can be produced by turbulent dissipation, shear due to the intense GC gravitational potential, and large-scale shocks (see, e.g., Rodríguez-Fernández et al. 2004; Güsten & Philipp 2004). Moreover, recent observations of the GC region in infrared transitions of H_3^+ by Goto et al. (2002) suggest that the GC CR ionization rate (ζ) is consistent with that of the disk $\zeta \sim 3 \times 10^{-17}$ s^{-1} cm^{-3}. It has also been suggested that an enhanced GC CR density might reveal itself through enhanced abundances of lithium and boron. These atoms can be formed through spallation reactions between cosmic rays and the ISM. Lubowich et al. (1998) have searched the GC region for hyperfine-structure lines of neutral Li and B with no success. From their detection upper limits, these authors suggest that the GC cosmic-ray energy density cannot exceed the disk value by more than a factor of 13.

Together these results ranging from γ-ray emission to the nondetection of lithium and boron provide strong circumstantial evidence that the GC cosmic-ray energy density is similar to that of the Galactic disk.

4. CONCLUSIONS

Utilizing new 74 and 330 MHz observations, we have discovered a new Galactic center feature, the diffuse nonthermal source. The DNS is extended along the Galactic plane with a size of $\sim 6° \times 2°$ and a spectral index steeper than -0.7. A minimum-energy analysis of the DNS requires that any *pervasive* magnetic field must be weak, of order 10 μG (and almost certainly $\lesssim 100$ μG). This field strength is 2 orders of magnitude less than the commonly cited value of 1 mG inferred from the assumption that the NTFs are tracing a globally organized magnetic field. We find that the minimum energy required to fuel the DNS can be supplied by the enhanced star formation, and hence supernova, rate within the Galactic center region.

The low global GC region magnetic field derived from this work is supported by a number of other lines of evidence. First, particle emission lifetimes in a 1 mG field, $\sim 10^5$ yr, are shorter than any plausible replenishment timescale for a long-lived source. If the global GC field strength is 1 mG, then the observed emission would imply a very low GC CR energy density. However, EGRET γ-ray observations (Mayer-Hasslewander et al. 1998; Hunter et al. 1997) indicate a GC CR energy density consistent with that measured in the Galactic disk. Light element (Li and B) abundance upper limits, H_3^+ detections, and consideration of molecular cloud heating are also all consistent with a normal Galactic plane cosmic-ray energy density in the GC.

This weak field picture is substantially different from the canonical one that has emerged over the past two decades for the "Galactic center magnetosphere" (e.g., Morris & Serabyn 1996; Güsten & Philipp 2004) wherein the entire Galactic center region (approximately bounded by the CMZ) has a globally organized strong magnetic field of order 1 mG. Together, the radio and γ-ray data yield a GC cosmic-ray energy density and magnetic field strength that are comparable to their disk values. Any departures in the energetics from the disk values result from the enhanced level of star forming and associated activity at the Galactic center, an even more extreme version of which may be the nuclear starburst in M82 (Seaquist & Odegard 1991). It is important to note that our analysis constrains the average magnetic field strength on size scales larger than our 74 MHz resolution of 125″ and *does not* preclude locally strong magnetic fields on smaller size scales.

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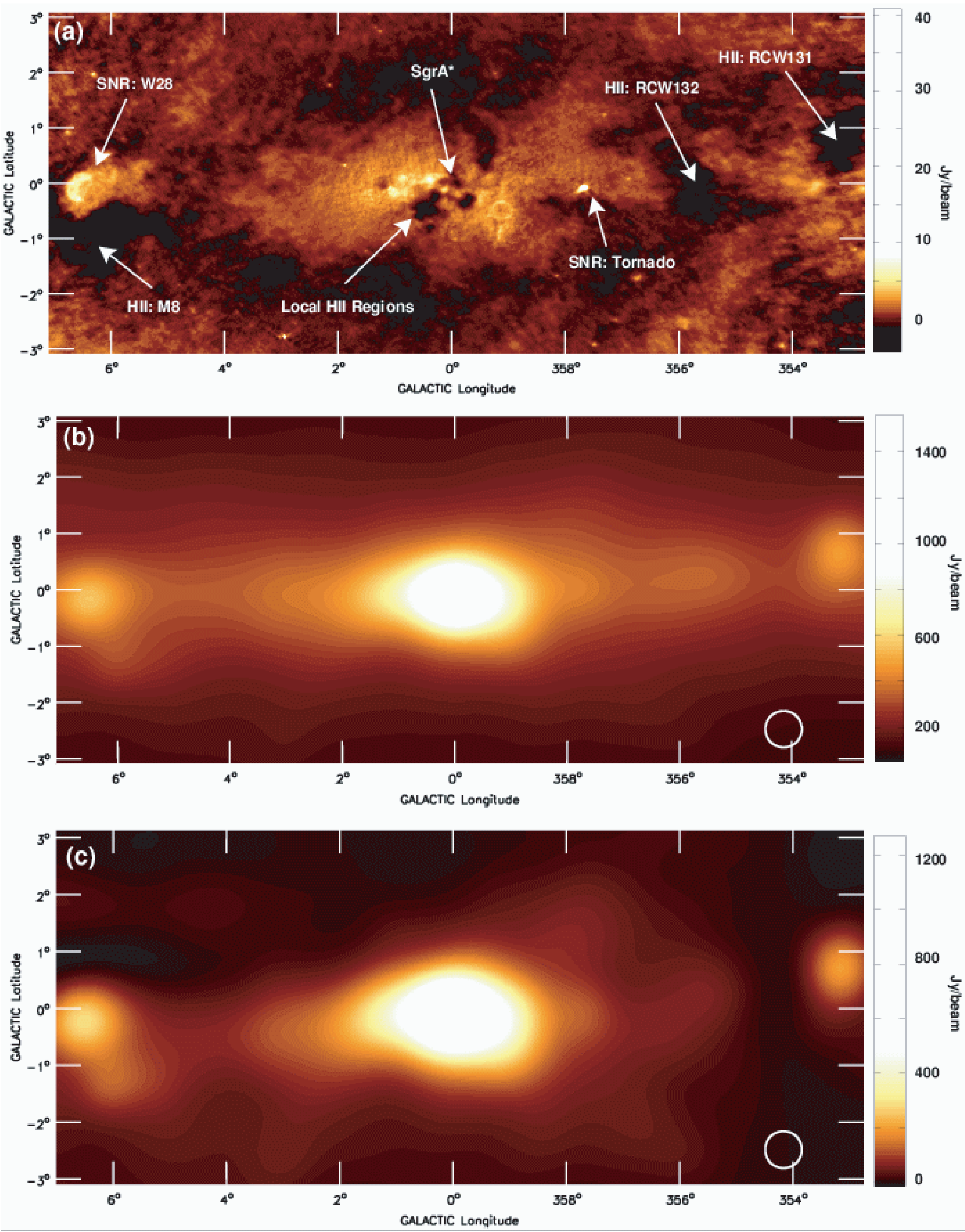

Fig. 1.—(*a*) VLA image of the Galactic center at 74 MHz with 125″ resolution. (*b*) GBT image of the Galactic center at 330 MHz with 40′ resolution (beam is shown in lower right corner). (*c*) Background-subtracted GBT image of the Galactic center region (beam is shown in lower right corner). Some of the brighter emission and free-free absorption sources are indicated in (*a*).