H II regions, infrared dark molecular clouds and the local geometry of the Milky Way’s nuclear star-forming ring

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ABSTRACT

Aims. To interpret the galactic center H II region complexes as constituents of a barred galaxy’s nuclear star-forming ring.

Methods. We compare 18cm VLA radiocontinuum, 8 – 22µ MSX IR and 2.6mm BTL and ARO12m CO emission in the inner few hundred pc.

Results. Galactic center H II regions are comparable in their IR appearance, luminosity and SED to M17 or NGC0, but the IR light distribution is strongly modified by extinction at 8-22µ, locally and overall. In Sgr B2 at l > 0.6° strong radio H II regions are invisible in the IR. In two favorable cases, extinction from individual galactic center molecular clouds is shown to have τ ≳ 1 at 8-22µ independent of wavelength. The gas kinematics are mostly rotational but with systematic ±30 – 50 km s⁻¹ non-circular motion. Sgr B and C both show the same shell and high-velocity cap structure.

Conclusions. The HII regions lie in a slightly-inclined ring of radius ≈ 180 pc (1.2°) whose near side appears at higher latitude and lower velocity and contains Sgr B. Sgr C is on the far side and both Sgr B and C represent collisions with material inflowing along the galactic dust lanes. Sgr E is a coincidental aggregation of field objects seen tangent to the ring’s outer edge. Most of the volume interior to the ring is probably devoid of dense gas and some emission seen at v=20-70 km s⁻¹ toward Sgr A lies outside it, in the ring.

Key words. interstellar medium – molecules

1. Introduction.

This is the third paper of a short series (Liszt, 2006, 2008) discussing the Milky Way’s inner galaxy gas distribution in the context of the characteristic features which are present in nominally similar barred external galaxies (Reynaud & Downes, 1999; Greve et al., 1999; Regan et al., 1999) and in models of barred galaxy gas flow (Fux, 1999; Regan et al., 1999; Regan & Teuben, 2004; Rodriguez-Fernandez & Combes, 2008). Inasmuch as possible, but without being overly reductive, we wish to meld the local data, with its unique galactic perspective and overwhelming wealth of detail, with a framework which has proved so successful in elucidating structure in other galaxies. The desirability of doing this seems clear, and an entirely similar view has recently been adopted by Rodriguez-Fernandez et al. (2006) and Rodriguez-Fernandez & Combes (2008). However, connections between Milky Way observations and those of other systems have been obscured by the complexity and richness of the local observations and by our unique perspective within the galactic disk. Some aspects of the Milky Way have been made to appear unique simply by our unparalleled vantage point and common features in barred galaxies have been missed in the Milky Way.

In the first two papers we discussed material associated with the large-scale bar dust lanes. We suggested that a series of enigmatic, highly-localized broad-lined molecular gas features should be associated with the shredding of molecular clouds at positions of gas uptake into the large-scale galactic dust lane shocks: in other galaxies such phenomena are visible as broad lines and velocity shifts across the dust lane (Reynaud & Downes, 1999) but the individual uptake events and their surprising and quite extreme vertical elongation (common to all the Milky Way events) are not discernible. The peculiar kinematic signature commonly identified with the Milky Way’s dust lane can be found in at least three distinct features in the northern hemisphere (see also Rodriguez-Fernandez et al. (2006)) and the temporal sequence associated with gas uptake and inward flow may perhaps be used to understand the vertical course of the bar gas flow.

In this work, we focus on the structure interior to the inner ends of the prominent bar shock dust lanes, in the more immediate vicinity of the nucleus. In other barred galaxies the star formation in this zone occurs within narrowly-defined nuclear star-forming rings (NSFR; see Kormendy & Cornell, 2004).
the Milky Way, this phenomenon is represented by the complex of sources Sgr A-E, the giant H II region-molecular cloud complexes at $|l| < 1.4^\circ$ corresponding to projected distance of some 200 pc from Sgr A*. However, owing to our viewing geometry, a ring morphology has been far from obvious; instead, the region has been generally characterized as the “central molecular zone” (CMZ) [Morris & Serabyn 1996] which in its most extreme form is described as being nearly filled with high density molecular gas. Here we suggest that the CMZ is actually rather hollow, as is typically the case in barred galaxies having prominent nuclear star-forming rings.

This paper considers the ring structure in detail, both locally within individual H II region/molecular cloud complexes, and overall. We compare the distributions and/or kinematics of three tracers, namely the L-band (18 cm) radiocontinuum emission, 8–22 $\mu$m IR emission and 3 mm CO emission. The organization of this work is as follows. Observational material, some of which is new, is discussed in Sect. 2. Section 3 gives an overview of the distribution of mid-IR and molecular emission in the inner ±200 pc and a detailed discussion of the individual off-nuclear H II region/molecular cloud complexes Sgr D, B, C, and E: in the most extreme case, the strongest radio H II regions in Sgr B2 are lost to extinction in the IR, even at 22 $\mu$m. In Sect. 4 we derive the extinction originating locally in a few especially-prominent infrared-dark (molecular) clouds (IRDC): consistent with previous results [Hildebrand et al. 2005; Nishiyama et al. 2008] and a plateau in the model interstellar extinction curves [Weingartner & Draine 2001], the extinction shows no decline over the MSX bands. In Sect. 5 we derive IR-radio spectra of the Sgr source complexes and their compact constituents, showing how the IR-radio continuum comparison can be used to infer high extinction when it is not obvious in the underlying source morphology. In Sect. 6 we discuss the global placement of sources in a putative ring, within which the non-circular motion and front-back inclination are just large enough to distinguish the near and far ring segments. Section 7 is a summary. Note that the Sun-center distance is taken as $R_0 = 8$ kpc so that 1′ corresponds to 2.33 pc.

2. Observational material considered

2.1. New observations

The observational material considered here comes largely from published sources, but it also includes a substantial component of previously unpublished large-scale mapping of 12CO emission from the present ARO (former NRAO) 12 m telescope on Kitt Peak, observed in 1995 May by the author. Maps were made in the vicinity of Sgr B and D at $0.5^\circ < |l| < 1.2^\circ$ and around Sgr E at $l = -1.2^\circ$. These are fully spatially-sampled data with 1′ spatial resolution, 1 MHz (2.7 km s$^{-1}$) velocity resolution and typical rms noise 0.1 K.

2.2. Previously published CO emission line data

Also shown here are maps drawn from the BTL galactic center CO survey [Bally et al. 1987] at 1.7′ resolution. For 13CO these data are on a 1′ grid with 1 MHz or 2.6 km s$^{-1}$ velocity resolution and typical rms 0.5 K. For 12CO the grid spacing is 30′ and the typical rms noise level is 0.15 K.

Table 1. MSX Bands and conversion from pixel values to Jy

| Band | wavelength | $X$ | $\mu$ | St Hz$^{-1}$ |
|------|------------|-----|------|-------------|
| A    | 8.28       | 5.53x10$^4$ |
| B    | 12.13      | 2.40x10$^4$ |
| C    | 14.65      | 2.66x10$^4$ |
| D    | 21.85      | 2.02x10$^4$ |

$X$ is the factor by which MSX pixel values or sums of pixel values should be multiplied to convert to Jy.

2.3. Nominal CO-H$_2$ conversion

Unless otherwise noted, velocity-integrated intensities of 12CO and 13CO in units of K-km s$^{-1}$, denoted respectively by $W_{12}$ and $W_{13}$, are converted to H$_2$ column density $N(H_2)$ assuming a typical galactic disk conversion $N(H_2) = 2 \times 10^{20}$ H$_2$ cm$^{-2}$ $W_{12}$, and $W_{12}/W_{13} = 6$ which is typical of galactic center material in the H II region complexes in our data and the BTL survey.

2.4. VLA L-band continuum

This is the data discussed originally by [Liszt 1992] and Liszt & Spiker (1995). It was taken in a 12.5 MHz band centered at 1616.4 MHz (a region of the spectrum subsequently lost to use by the Iridium satellite constellation) in the VLA C and D configurations and has spatial resolution 13″×23″.

2.5. Radio recombination line data

The data, shown here in Fig. Y, were taken in 1990 at the NRAO 43m telescope in Green Bank in 1990, and were first shown by Liszt (1992).

2.6. MSX maps

The Mid-Course Space Experiment (MSX, Price et al. 2001) mapped the galactic center region at 21″ resolution on a 6″/pixel grid in four bands at center wavelengths ranging from 8 $\mu$m to 22 $\mu$m. These data are provided as specific intensity in units of W (m$^{-2}$sr)$^{-1}$. These can be expressed in Jy at individual pixels using the conversion factors given in Table 1 corresponding to the solid angle of 6″ pixels and the stated photometric bandwidths of the MSX spectral bands expressed in Hz. Figure A.1 in Appendix A illustrates the 50%–response MSX bandwidths graphically on curves of the extinction cross-section per H atom for galactic dust [Weingartner & Draine 2001].
2.7. A word about the figures used in this version of the paper

The postscript versions of several of the figures created for this paper are intractably slow to load on-screen and all the figures have been replaced here by serviceable, more compact versions suitable for pdflatex, which will not be used in the published paper. The striations in Fig. 2 and 11 are artifacts of image conversion and will not appear when published.

3. Structure of the inner region and individual sources

The top two panels of Fig 1 show the mid-IR brightness in the MSX A and E-bands (around 8.3 and 21.8 µ, respectively, see Table 1 and Fig. A.1). Superposed in each case are contours of the velocity-integrated intensity of $^{13}$CO, $W_{13}$, at $|v| \leq 100$ km s$^{-1}$ from the survey of Bally et al. [1987]. Shown at bottom in grayscale is the same distribution of $W_{13}$. The 0.9° radius which contains most of the IR brightness projects to 125.6 pc across the line of sight at a Sun-center distance of 8 kpc (1′ corresponding to 2.33pc). The outlying sources Sgr D and Sgr E at $|l| > 1.15°$ (> 160 pc) which define the outer edge...
of the nuclear star-forming region are not shown in Fig. 1 but will be discussed separately in this Section along with the other sources.

It is clear from observations of galactic H II region complexes (see Povich et al. (2007); Watson et al. (2008) and Appendix C) that the shorter wavelength panel in the middle of Fig. 1 mainly shows very hot dust interior to the ionized region so that the Sgr B, A, and C H II regions at 0.7°, 0.2° and -0.5°, respectively, appear with greater clarity. The longer wavelength panel at the top of Fig. 1 shows more broadly-distributed material within the ambient neutral gas, and especially (as discussed below) at the H II region/molecular gas interfaces.

All of the Sgr H II regions lie in a rather thin band running parallel to the galactic equator between $b = -0.05°$ (the latitude of Sgr A*) and $b = -0.10°$). However, the large-scale distributions of molecular gas and IR light are noticeably bowed, with most of the emission occurring well below the galactic plane at the extremes in Fig. 1. The IR distribution in the uppermost panel at $8\mu$ is clearly affected by infrared dark clouds visible in CO, especially in an extended distribution of foreground extinction at $l > 0.25°$ shrouding Sgr B. The downward slant of the upper edge of the $8\mu$ emission at positive longitude in Fig. 1 at top is more obviously an artifact of this extinction, but extinction is also visible, albeit somewhat more faintly, at the northern edge of the $8\mu$ light distribution at negative longitude where it also bows downward. It is straightforward to visualize how the accumulation of absorption near the ends of a ring-like distribution might be responsible for this, when the ring is slightly inclined so that the nearer portions are seen at higher latitude. However, much of the extinction is actually indigenous to the same H II region complexes which are responsible for the IR light in the first place.

Extinction in the Sgr B complex around $l = 0.6°$ largely but not exclusively (see Sect. 3.2) arises in molecular gas at $0 \text{ km s}^{-1} < v < 50 \text{ km s}^{-1}$ and one especially clear case of extinction by this gas is seen just above the equator between Sgr A and B at $l \approx 0.25°$. Another prominent extinction arising in gas at negative velocity appears just above the Sgr C H II region at $l = 359.5°$ and both of these cases are discussed in detail in Sect. 4. It is less obvious that emission at the longest wavelength IR map in the middle panel is significantly affected but the extinction of the individual IRDC shows no obvious wavelength dependence from 8-22$\mu$ and some foreground extinction at 22$\mu$ which is not apparent from the morphology may be inferred from the spectra which are discussed in Sect. 5.

The general question of how the material represented in Fig. 1 is actually distributed in space is left for Sect. 6 but the appearance of the molecular gas at bottom is clearly rather looped and somewhat hollow at negative longitudes. At positive longitudes the molecular gas in the Sgr B complex is so bright and so extended that the z-height of the material overall is otherwise obscured. The expectation is that the star forming regions in a strongly-barred galaxy like the Milky Way will be situated in a radially-narrow, approximately circular, mostly-rotating ring and the inference of a ring geometry for the Milky Way gas is discussed in Sect. 6. The nuclear region in our Galaxy is the only one whose vertical structure is distinguishable and, at least at negative longitudes, it appears that a slight scalloping may have displaced the front and back gas portions, so that they are not projected on top of each other. In Sect. 6 we also discuss how the front and back ring portions are distinguishable kinematically, owing to departures from pure circular motion.
The structure of the individual H II region/molecular cloud complexes is discussed in the following subsections, progressing from highest (Sgr D) to lowest (Sgr E) galactic longitude.

### 3.1. Sgr D

The radiocontinuum properties of Sgr D were described by Liszt (1992) and Mehringer et al. (1998) and a Band E MSX image appears in Conti & Crowther (2004). The source is visible at $l_2 \mu$ (Blum & Damineli 1999). Although it lies at the “right” galactic latitude, its location within the ring is contentious.

Figure 2 shows the source morphology in the radio and MSX IR bands. Sgr D consists of an H II region to the North, visible at both radio and infrared wavebands, and an adjacent shell radio supernova remnant (radio SNR) which appears only in the radio (see also Gray 1994). The H II region is associated with a peak in the $^{13}$CO emission having $W_{13} \approx 50$ K km s$^{-1}$ and line brightness $5 \times 10^5$ K at $v \approx -17$ km s$^{-1}$ (see also Fig. 2) near the recombination line velocity (Fig. B.1). The nominal mass of associated molecular material (see Sect. 2.2) is $\approx 2 \times 10^5 M_{\odot}$.

The bright $^{13}$CO peak most likely represents a region of interaction between the ionized and neutral gas distributions; overall the molecular gas has a shell-like appearance which cradles the southern portions of the extended thermal radiocontinuum distribution. Portions of this shell and the wishbone structure to the north are visible in the MSX Band A emission at top right in Fig. 2. Longer wavelength IR emission in MSX Band E is more nearly dominated by hot material in the compact H II region but extended structure is also visible, especially to the north. Although it is not obvious that the IR source morphology is affected by extinction, the global spectrum shows some deficiency of IR emission compared to the radiocontinuum, which in other cases results from foreground extinction of the IR (see Sect. 5).

The placement of Sgr D along the line of sight remains somewhat of a puzzle owing to its recombination line velocity of $-9$ km s$^{-1}$ (see Fig. B.1). Interpretation of absorption measurements has placed it at Conti & Crowther (2004) or beyond Lis (1991) Mehringer et al. (1998) the galactic center. In particular, Lis (1991) argued for a position outside the bulge based on the narrowness of the mm-wave emission lines from the nearby molecular gas. Examination of molecular emission over a larger region does not provide much context for placement of Sgr D, whose velocity is distinct from those of other similarly-narrow but spatially-extended ridges of emission in the region. Owing to the extraordinary kinematic complexity of the region, which falls between the nuclear ring and the innermost uptake event into the dust lane at $l=1.3^\circ$ (Liszt, 2006), there actually is gas at rather low $|v|$ which is undeniably part of the inner-galaxy gas.

Within the ring it is expected that stars and natal gas will separate and phase mix with other ring members after the stars form, making it less likely that the evolved progenitor of the Sgr D SNR and the O-stars in the H II region actually formed from the same cloud. Moreover, it is possible that the SNR is an interloper in the vicinity of the H II region and molecular cloud (if all are actually sited within the ring), so that proximity still does not demand a physical association. However, if an association between the H II region and SNR could be demonstrated, it would have interesting consequences for star formation mechanisms within the ring gas. A physical association between the H II region and SNR could be investigated by searching for 1720 MHz OH maser emission around the SNR.

### 3.2. Sgr B

The presence of extinction in the Sgr B source complex around $l=0.6^\circ$ is apparent in Fig. 1 but its full influence can better be seen by comparing source structure in the radio and IR continuum as in Fig. 3. Simply put, the strongest H II regions visible in the radio (at $l \approx 0.6^\circ$) are mostly absent at both 8$\mu$m and 22$\mu$m. Although the physical structure of Sgr B arises from an interaction between the neutral and ionized gas (which partly overlap in velocity and are physically co-mingled), the absence of the strong radio H II regions in the IR can only result from near-complete attenuation of the IR flux.

The radiocontinuum and MSX Band E images are shown in Fig. 4 along with the integrated $^{13}$CO emission at velocities above and below 50 km s$^{-1}$. The higher velocity emission, which overlaps the recombination line velocities (62 km s$^{-1}$; see Fig. B.1), is shown over the radiocontinuum with its clear image of the H II regions: lower velocity emission, from more extended gas responsible for the IR extinction, is overlaid on the MSX Band E image in which the extinction is the most important aspect of the extended neutral gas distribution. The
IR and radio continuum emission largely exists inside a cavity in the lower-velocity molecular gas, which is partly filled in by material at the higher velocity. The brightest compact radio H II regions which are so heavily extincted are seen projected squarely against very bright CO emission at comparable velocity, and must be behind the molecular gas.

The low-velocity shell and high-velocity cap have been interpreted as a cloud-collision in a series of papers by Hasegawa and his collaborators (Hasegawa et al., 2008; Sato et al., 2000; Hasegawa et al., 1994); this explanation accounts for many of the properties of the regions chemistry and masers. Sgr B2 can probably be identified with the contact region between the star-forming ring and gas inflowing in the dust lanes in the nuclear regions of the Milky Way Bar (e.g. Regan & Teuben (2003) and Fig. 9 of Regan et al. (1999) or recent discussions in Liszt (2006) and Rodriguez-Fernandez & Combes (2008)). A similar spatial and kinematic shell and cap distribution of the CO emission is also seen in Sgr C (see immediately below).

3.3. Sgr C

Although far less active than Sgr B, the Sgr C H II region near \( l = 359.45^\circ, b = -0.1^\circ \), at \( v = -60 \text{ km s}^{-1} \) (see Fig. B.1) is positioned nearly symmetrically in space and velocity. The radiocontinuum structure has been discussed by Liszt (1985), Lisbor et al. (1991) and Liszt & Spiker (1995) and maps of the molecular gas were discussed by Liszt & Spiker (1995) and Staguhn et al. (1998).

The IR and radiocontinuum structure of Sgr C is shown in Fig 5. In the radio, Sgr C consists of extended, round, thermal emission from an H II region powered by one or a small number of O-stars Liszt & Spiker (1995) and an adjacent, elongated, non-thermal filament which was the first such object to be seen outside Sgr A. Partly based on the structure in Sgr C Yusef-Zadeh (2003) argued that non-thermal filaments in the galactic center are caused by interaction of young stellar clusters and ambient dense gas, but Roy (2003) argued that the H II region and filament are separated along the line of site and not physically related, owing to differences in their H I absorption spectra.

Based on the limited \(^{13}\text{CO}\) mapping shown in Fig. 5 Liszt & Spiker (1995) noted merely that the Sgr C H II region is placed between the two molecular emission distributions at \(-125 < v < -85 \text{ km s}^{-1}\) and \(-85 < v < -45 \text{ km s}^{-1}\). It has been something of a puzzle why gas at such widely separated velocities should all brighten near Sgr C, but larger-scale imaging of the molecular gas (Fig. 6) shows that the kinematic structure is actually very like that in Sgr B: a smaller core of emission near the recombination line velocity (-65 km s\(^{-1}\); Fig. B.1) is surrounded by a partial ring of gas which is displaced in velocity. Apparently, Sgr C is actually physically associated with both kinematic components of the gas and, like Sgr B, it may represent the interaction of inflowing material in the dust lane with pre-existing material in the SFR.

MSX Band E emission coincides with the radio H II region and arises from heated material within it. The more extended and extincted MSX Band A emission occurs between the blue-shifted gas to the North and the cloud at the H II region velocity; only a rather minor portion of the MSX Band A light overlaps the H II region. As such it might be associated with either of the two kinematic components. Although there is weaker emission at the H II region velocity across the prominent Band A extinction north of Sgr C, the CO emission around -100 km s\(^{-1}\) is much stronger and similar in appearance to the region of IR extinction. The extinction likely arises in the lower velocity gas (see just below and Fig. 6). As noted by Roy (2003) there is H I absorption at -100 km s\(^{-1}\) toward the H II region. The extinction is discussed in more detail in Sect. 4.
3.4. Sgr E

The radiocontinuum structure and recombination line kinematics of Sgr E around $l = -1.3^\circ$, $b = -0.1^\circ$, $v = -215$ km s$^{-1}$ (Fig. B.1) have been observed by Liszt (1992), Gray et al. (1993) and Cram et al. (1996). At a maximum projected radius of 195 pc corresponding to $l = 358.6^\circ$, Sgr E marks the outer boundary of the galactic center star-forming ring in both galactocentric radius and velocity. Sgr E lacks a symmetric counterpart at positive longitude, especially as regards the velocity.

Sgr E is unusual among the named galactic center H II region complexes in being devoid of extended emission. The very high observed velocities imply that the sources are observed near the sub-central point, in which case the line of sight velocity gradient is small and the sources could be distributed over a long path where the line of sight is tangent to the edge of the ring. Observing Sgr E may afford the opportunity to study a sample of somewhat older (i.e. B-type) “field” stars which have phase-mixed around the ring but the Sgr E source complex is not a physical entity.

The IR and radiocontinuum structure of Sgr E is shown in Fig. 7. Nearly all of the radiocontinuum sources have IR counterparts. The radiocontinuum source at $l = 358.6^\circ$, $b = 0.06^\circ$ lacks such a counterpart and was singled out by Cram et al. (1996) for lacking a radio recombination line: It is probably an extragalactic interloper and perhaps a useful source for acquiring comparison absorption spectra through the galactic disk.

The nominal total H$_2$ mass represented in Fig. 7 is $1.1 \times 10^6 M_{\odot}$ (see Sect. 2.2).

4. IRDC and the CO-H$_2$ conversion factor

Extinction of the IR radiation by darker foreground material is apparent in Fig. 1 and two especially well-defined cases of association between molecular emission and extinction in the MSX bands are illustrated in Fig. 8 and 9.

4.1. The IRDC near Sgr C

A very prominent IRDC seen just north of Sgr C was noted in Sect. 3.3 and illustrated in Fig. 5. It probably originates in gas seen in CO emission at $-135 < v < -85$ km s$^{-1}$ (also see Fig. 6). As seen in Fig. 6 the peak CO brightness associated with the IRDC near Sgr C is $W_{CO} = 480$ K km s$^{-1}$. Fig. 8 at top shows a latitude cut across the IRDC in MSX Band A. The peak absorption optical depth is straightforwardly estimated as 0.75, corresponding to an extinction of 0.81 mag. Extinction is probably present at 22$\mu$, illustrated by the transverse cut in the lower panel of Fig. 8 which shows a clear dip at the expected latitude. The extinction at both wavelengths must be comparable but determination of the spectrum of the extinction is better left for the even better-defined extinction between Sgr A and Sgr B.

4.2. The prominent IRDC between Sgr A and Sgr B

MSX fluxes over a spatial cut across the especially prominent feature between Sgr A and Sgr B around $l = 0.25^\circ$ in Fig. 1 are shown in Fig. 9. The path of this cut runs at a 45$^\circ$ angle with respect to the galactic equator, along the short axis of the absorption, from $l = 0.4^\circ$, $b = -0.1^\circ$ to $l = 0.2^\circ$, $b = +0.1^\circ$. Shown at top is a strip across the full extent of the cut in MSX Band A, illustrating how a baseline was established to gauge the strength of the absorption. At bottom in Fig. 9 are the absorption and optical depth (inset) profiles which ensue. They are lower limits because we have assumed that the absorbing material is black and we have not accounted for contamination by unrelated foreground emission.

The extinction is rather gray, with no obvious variation with band wavelength and a peak optical depth of 1.3 in all bands, corresponding to extinction of 1.4 mag. Wavelength-independent extinction in this region of the spectrum has recently been noted by Indebetouw et al. (2005) and Nishiyama et al. (2008) and is broadly consistent with a plateau in the interstellar extinction in the dust models of Weingartner & Draine (2001). The overlap of the MSX 50% photometric bandwidths with the wavelength-dependent extinction coefficients of Weingartner & Draine (2001) is shown in Fig. A1.

At least approximately, an extinction coefficient C’/H = $1.3 \times 10^{-23}$ cm$^2$/H can be attributed across the MSX A-E bands. This implies column densities of 0.75/C’ = 6 $\times$ 10$^{22}$ cm$^{-2}$ and 1.3/C’ = 1.0 $\times$ 10$^{23}$ cm$^{-2}$ for the IRDC near Sgr C and around $l = 0.25^\circ$, respectively, given their optical
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depths of 0.75 and 1.3. These then correspond to visual extinction
\( A_V = 6 \times 10^{12} R_V / 5.8 \times 10^{21} = 32.1 (R_V/3.1) \) mag
and 53.4 (\( R_V/3.1 \)) mag. Alternatively, \( A_V / A_{MSX} = 39.4 (R_V/3.1) \)
given the common assumption that \( E_{B-V} / \text{mag} = N(H)/5 \times 10^{21} \mathrm{cm}^{-2} \) (Savage et al., 1977).

As suggested by the images Fig. 1, more detailed images of CO emission (not shown here) indicate clearly that the material responsible for the absorption at \( l = 0.25\degree \) is at \( 0-50 \) km s\(^{-1} \), i.e. it is the same material responsible for the extinction around the Sgr B complex as discussed above in Sect. 3.2. At the deepest trough in the IRDC, the peak integrated CO brightness in the 1.7\degree resolution BTL survey is 505 K km s\(^{-1} \), which is some 400 K km s\(^{-1} \) higher than at adjacent positions outside the IRDC. This is equivalent to a CO-H\(_2\) conversion factor \( N(H_2)/W_{CO} = 0.5 N(H)/W_{CO} = 1.25 \times 10^{20} \mathrm{H} (R_V/3.1) \mathrm{cm}^{-2} \). A consistent result is also obtained for the feature near Sgr C. At this level of accuracy the CO-H\(_2\) conversion factor for galactic center gas is at most modestly below that for material near the Sun.

### 4.3. Sgr B

The IR extinction in Sgr B is so very spatially extended that a reliable baseline flux measurement did not seem feasible. The integrated CO intensities for the lower-velocity gas responsible for the IR extinction are shown in Fig. 6 and Fig. 7 and are somewhat larger than are present in the two IRDC just discussed, 140-160 K km s\(^{-1} \) for \(^{13}\)CO and 800 - 1000 K km s\(^{-1} \) for \(^{12}\)CO. As discussed in Sect. 6, comparison of radio and IR fluxes suggests that the very strongest radio H\(_\mathrm{II}\) regions in the eastern part of Sgr B are behind material with optical depth of order 4 in the MSX bands.

### 5. Global and compact H\(_\mathrm{II}\) region source spectra

Figure 10 shows IR-radio spectra of many sources in the galactic center region, extracted from the MSX and 18cm VLA maps. All of the radiocontinuum fluxes have been scaled upward by a uniform factor of 250 to allow convenient viewing. The fluxes shown are simple pixel sums over identical regions in all bands (for each source), without correction for the background.

Also shown in Fig. 10 are comparison spectra for two galactic H\(_\mathrm{II}\) regions outside the center, namely, M17 (Povich et al., 2007) and N10 (Watson et al., 2008). IR fluxes for these objects were also extracted from the MSX maps but the radio fluxes are derived from the MAGPIS survey (Helfand et al., 2006), scaled by the frequency dependence of optically-thin
free-free emission to account for the slight difference in frequency (1390 vs. 1618 MHz). Except at the upper left, the overall flux scale of the M17 spectrum shown in the various panels of Fig. 10 is arbitrary, because only a comparison of slopes is needed. At the upper left, the M17 fluxes are absolute but have been rescaled to 8 kpc distance (from 1.6 kpc) and (as noted there) further divided by a factor of two to facilitate comparison. The spectrum of N10, a galactic H II region bubble at a distance of 4.9 kpc, is also shown at upper left, without rescaling. The morphology of N10 is generic; it strongly resembles Sgr C (see Fig. C1 and Appendix C).

In the following discussion, the behavior of the larger and more compact sources is discussed separately. Although the Sgr B, C, and D regions as a whole strongly resemble M17 and N10, allowing for the straightforward possibility of some additional extinction in the galactic center sources in the IR bands, the spectra of compact sources are coherent within individual complexes but rather different from one to another, especially between the two halves of Sgr B.

5.1. Extended sources

Integrated spectra of the extended galactic center regions Sgr B, C, and D are shown at upper left; they resemble those of M17 and N10 in form and bracket them in absolute flux. This establishes that the galactic center sources are very much like galactic disk H II regions, as long as extinction in the IR (which must be higher for the nuclear ring sources) is not too strongly wavelength dependent from 8-22 µm. However, in the case where the foreground extinction is obviously the greatest, Sgr B at l > 0.6°, the radiocontinuum flux is conspicuously large (by a factor of five) relative to M17, suggesting that the great majority of the total IR flux of the eastern half of Sgr B is absent at below 22 µm. Sgr D also has a somewhat large radio/IR flux ratio, but somewhat less in comparison with N10, than with M17. The slight difference in IR/radio flux ratios between M17 and N10 could represent normal variation in the H II region population, but N10 will have suffered higher extinction than M17 owing to its greater distance (4.9 vs 1.6 kpc) and also because it is inside the galactic molecular ring.

Overall the comparison with M17 seems quite fair and M17 should not be too heavily extincted by intervening unrelated gas in the MSX bands. However, given that all of the sources in the galactic center (not just those in Sgr B2) probably suffer from some significant foreground extinction, the similarity of their spectra to that of M17 implies that the extinction must be rather gray, as previously indicated by the individual IRDC discussed in Sect. 5 and illustrated in Figs. 8 and 9 (see Indebetouw et al. (2005) and Nishiyama et al. (2008)).

5.2. Sgr B at l > 0.6°, Sgr B2

Spectra of compact sources in Sgr B are shown in the right-hand panels of Fig. 10. The systematics of spectra from the more heavily-extincted sources in Sgr B2 at l > 0.6° in the lower right panel seem especially clear: the IR spectra steepen noticeably as the sources brighten and the 22µm/radio flux ratio increases. For one of the sources (#7), and in particular that source which is closest to Sgr B1, the IR/radio flux ratio actually reverses relative to M17, which is a characteristic of nearly all of objects in Sgr B1.

This steepening belies the similarity with M17 and N10 seen in the large in the upper left panel of Fig. 10 and complicates both the IR/radio flux comparison and the inference that the IR extinction is gray. To flatten the M17 or N10 spectra across the MSX bands would require some 17 or 5 times higher extinction at 22µm than at 8µm, respectively. To ameliorate this situation, we suggest that the observing geometry is at least partially responsible. The weakest Sgr B2 IR source shown is probably absent in the MSX data and the flat-spectrum measured flux is a mixture of noise and foreground haze (in the discussion of Sgr E in Sect. 6.3 we note that IR sources which lack radio emission entirely have flat spectra across the MSX...
5.3. Sgr B at \( l < 0.5^\circ \), Sgr B1

Spectra of sources in and just West of Sgr B1 at \( l \leq 0.5^\circ \) are shown at upper right in Fig. 10. Note that the Sgr B1 sources are brighter in the IR than those Sgr B2, despite the fact that Sgr B2 is known as the region of greater star formation activity judged from the radio emission. The IR spectra of the galactic center sources in the upper right panel of Fig. 10 resembles those of M17 or N10, none being as flat as was seen in Sgr B2. However, the radio/IR flux ratios differ notably from M17, N10 and Sgr B2, being rather smaller. Some of this variation in radio/IR flux ratio can probably be explained by optical depth effects in the radiocontinuum, if the optical depth is appreciable.

5.4. Sgr E at \( l < 1.1^\circ \)

Spectra of sources in Sgr E, which is largely devoid of extended flux in the radiocontinuum, are shown at lower left in Fig. 10. IR spectra of the Sgr E sources generally resemble M17 and those in Sgr B1, and the radio/IR flux ratios are also much like those in Sgr B1 and unlike those in Sgr B2. The Sgr E sources are brighter in the IR and weaker in the radio than those in Sgr B2.

IR spectra were also extracted for three sources (nos 7-9, shown dashed and in blue) which show no obvious 18cm radiocontinuum at all; the radio fluxes reported for these sources are the totals within the boundaries of the respective IR images. These sources are characterized by flatter MSX spectra.

6. Is there a CMZ in the Milky Way, or only a NSFR?

How then is the gaseous material in the inner \( \pm 175 \) pc actually distributed? From our vantage point near the mid-plane the 8\( \mu \) light distribution in Fig. 1 is largely undifferentiated while the 22\( \mu \) emission is at the other extreme, showing the seemingly isolated Sgr B, A, and C source complexes. However, the \( ^{13}\)CO distribution in Fig. 1 is somewhat hollow and loop-like at negative longitudes and the kinematics support this impression. Even from the crude sampling of recombination line emission in Fig. B.1 it is apparent that the profiles are narrow compared to the span of the rotational pattern across the central region.
longitude and meeting the locus of the Sgr C recombination lines at $l=-0.5^\circ$, $v=-60$ km s$^{-1}$.

An economical description of this behaviour puts the gas into a ring (or pseudo-ring comprised of arm segments which is slightly tipped out of the galactic plane, so that the front and back portions are displaced in latitude. The outer size of the ring and its rotation speed are set by the locus of Sgr E at $l=-1.25^\circ$ corresponding to 175 pc, with a rotation speed of 220 km s$^{-1}$ (since the ring is viewed tangentially). The line of sight inclination is small, $3.2^\circ$, i.e. a vertical displacement of $\pm0.07^\circ$ across a diameter of 350 pc. The near and far sides are also separated kinematically by a substantial ($\pm40-50$ km s$^{-1}$) component of non-circular motion, perhaps indicating an elliptical shape to the ring. The ring in the Milky Way bar is somewhat on the small side, but not impossibly so,

If it can be decided which of the kinematic branches is the near side, the sense of the non-circular motion and the inclination follow directly and a good description of the geometry and kinematics can be made. In the context of the discussion here, the prominence and placement of the IR extinction at $l>0.2^\circ$ suggest that the near branch of the ring is that which is seen at higher latitude and which includes Sgr B: Sgr C is then located on the ring portion seen behind the center. The same assignment of the nearer segment of the ring was noted earlier (Sect. 3.1) based on the shape of the global 8$\mu$m light distribution. This is the same assignment made by Sofue (1995) and repeated by Sawada et al. (2004) based on the kinematics of molecular absorption lines. It accounts for the presence of absorption at -100 km s$^{-1}$ in the vicinity of Sgr C, even if gas within the Sgr C complex at like velocities is not responsible (see Sect. 3.3).

Nonetheless the ring description is incomplete inasmuch as it begs the question of the gas in Sgr A, which is believed to reside near the center, but coincidentally occurs in a velocity range (20-70 km s$^{-1}$) which is manifestly present along the far side of the ring around $l=0^\circ$ (see the lower panel of Fig. 1; Sofue (1995) assigned the 50 km s$^{-1}$ gas around Sgr A to a separate arm). Given the appearance of the rings in other galaxies (which do not support the idea that the ring in the Milky Way bar is a separate arm) this suggests, in the context of the ring description, that Sgr A is part of a ring around the Milky Way bar, but not the same ring as that around Sgr B and C.
Way would fortuitously have a huge gap just behind Sgr A) it seems unavoidable that some portion of the material which is presently ascribed to Sgr A and the vicinity of the center must instead arise in the ring.

Deciding which gas in Sgr A is actually central, and how much dense gas exists interior to the ring at all, are challenges for the future. But if the Milky Way is like other galaxies the region interior to the ring may be largely devoid of dense gas and the description of the material as residing in a "central molecular zone" may be somewhat misleading. The molecular gas distribution presents a solid face in $^{12}$CO (not so much even in $^{13}$CO, see Fig. 1) from our vantage point in the galactic plane, but it is only the thin annular region of the ring which is actually occupied by the dense, warm, turbulent molecular gas which observationally comprises the CMZ.

7. Summary

Nuclear star-forming rings in barred galaxies are ongoing starbursts, fed by inflow of material along the dust lanes (Kormendy & Cornell 2004). The inward flow is typically staunched by resonant phenomena (Regan & Teuben 2003, 2004) at a narrow ring (of radius 100 - 1000 pc) where the continued introduction of new gas at high velocity keeps the density and pressure high, and where the continuing but episodic (Liszt 2006) interaction of fresh and previously-accumulated gas induces rapid star formation through such mechanisms as cloud-cloud collisions (Hasegawa et al. 2008).

The presence of an approximately 200-pc radius ring naturally accounts for many of the properties which have been attributed to molecular gas in the inner region or central molecular zone (Morris & Serabyn 1996) of the Milky Way – high mean density, thermal pressure and large turbulent motion seen over a very extended region around the center – but without actually filling the interior volume, accomodating yet other, more diffuse constituents of the galactic center ISM such as the diffuse metastable $H_3^+$ observed by Oka et al. (2005). Dense molecular gas, especially in the Sgr A complex, may exist interior to the ring, but conversely, some of the gas at 10-50 km s$^{-1}$ seen against Sgr A is probably in the ring (see just below and Sect. 6).

In this work, we compared the observed distributions of the IR and (radio) L-band continuum and molecular gas in order to describe the structure and some of the processes at work in the Milky Way’s nuclear ring. For the processes, we noted (Sect. 3.2) that Sgr B2 has already been described as a cloud-cloud...
collision and we described the particular morphology which led to this hypothesis, a high velocity cap projected against a broader molecular gas shell at lower velocity surrounding the Sgr B H II regions. We showed (Sect. 3.3) that Sgc C has similar kinematics, which accounts for the puzzling brightening of CO at widely-separated velocities in its direction. Sgr B and C are seen at very similar separations 0.5°-0.6° from the center and have similar velocities. In terms of bar dynamics, cloud-cloud collisions in Sgr B and C would represent the contact points near the inner ends of the bar dust lanes where material already in the ring interacts with inflowing or sprayed gas.

The H II region complexes are all composite, but the apparent groupings in Sgr D (Sect. 3.1) and Sgr E (3.4) may be unphysical. The Sgr D H II region at \( l = 1.1° \), \( v = -10 \) km s\(^{-1} \) cannot be proven to be in the galactic center nor is there direct evidence that it and the immediately adjacent (osculating, even), similarly-sized SNR are associated. Unfortunately, searches for tracers which would reveal the systemic velocity of the remnant have been unsuccessful. Sgr E seen at the presumed negative longitude extremity of the ring at \( l \lesssim -1.2° \), \( v < -200 \) km s\(^{-1} \) is certainly in the nuclear region but the implied tangential viewing geometry will cause unrelated and spatially-separated material to appear at similar velocity. It seems telling that Sgr E is a collection of discrete objects with little extended flux or apparent structure and rather modest H II regions powered by B-stars, i.e. field objects.

The appearance of the galactic center in the 8-22\( \mu \) IR MSX bands is strongly affected by extinction and the MSX bands fall in something of a plateau in the otherwise steady decline of extinction with increasing wavelength (Sect A.1, Fig. A.1). We began by noting (Sect. 3, Fig. 1) that the large-scale distribution of 8\( \mu \) light is bowed because it is preferentially extincted at its northern edge and toward its extremities. This immediately suggested a ring distribution of the extincting material with a slight upward inclination of the near side. The presence of such a tilt in the ring is also seen kinematically because the front and back ring portions have a systematic separation in latitude and velocity at most longitudes (see below and Sect 6).

We extracted the apparent extinction of prominent IR-absorbing material near Sgr C and between Sgr A and B. Especially in the latter the depth of the extinction (\( \tau = 1.35 \)) does not vary noticeably over the MSX bands, indicating that the extinction generally is indeed gray. Another indication that the extinction is gray comes from the overall similarity of IR spectra of galactic center and galactic disk H II regions, because the former are much more heavily extincted but are not seen to be reddened.

We also extracted the 8–22\( \mu \) spectra of the H II region complexes and their constituents (Sect. 5 and Fig. 10), and showed that globally, the spectra and apparent luminosities of galactic center sources are like those of disk objects such as M17 and N10. However, there is also evidence of strong IR extinction, because the ratio of radio L-band (18cm) to IR flux is much larger in Sgr B and somewhat larger even in Sgr D. Within Sgr B, the extinction of Sgr B2 at \( l > 0.6° \) behind the high-velocity cap signifying the cloud collision is so great that the strongest radio H II regions are simply absent in the MSX maps. Overall, the galactic center sources resemble M17 or N10 in their IR spectra but there is considerable variation of the radio/IR flux ratio even when extinction cannot obviously be fingered as the culprit. This probably calls for detailed modelling.

Last, we discussed the ring morphology and kinematics (Sect. 6). We discussed how the kinematic patterns of the CO emission fall into narrow-lined branches within the overall velocity envelope (i.e. are ring like) such that the gas, although mostly rotating at 200-220 km s\(^{-1} \), also has 30-50 km s\(^{-1} \) non-circular motions which cause the near and far portions to appear at different velocity at the same longitude. One portion of the ring therefore shows substantial positive velocities over the longitude range of the Sgr A complex, where much of the molecular emission usually attributed to the immediate vicinity of the center has always, to some general puzzlement, appeared at \( v = 20-40 \) km s\(^{-1} \). Some of this material probably originates in the ring, well away from the center, because there is no obvious reason to expect a complete gap in the ring over the approximately 0.2° extent of the Sgr A complex.

The ring portions are separated in velocity and displaced in latitude, consistent with the first impression gained from the bowing of the overall distribution of IR light in the presence of prominent extinction, whereby the front side of the ring is inclined slightly upward (Sect. 3). Viewed in detail (Fig. 11), the blue-shifted branch of the ring gas appears at higher latitude and intersects the velocity of Sgr B2 H II recombination line emission at positive longitude, 60 km s\(^{-1} \) at \( l \gtrsim 0.6° \). The red-shifted branch at lower latitude serves a similar role for Sgr C (\( v \sim 60 \) km s\(^{-1} \) at \( l = -0.5° \)) and includes the positive-velocities present across the region of the Sgr A complex. Therefore, Sgr B and Sgr C are on opposite front-back portions of the ring and Sgr B, which lies in the higher-latitude branch (responsible for the prominent extinction), falls on the near side, as has generally been assigned in the past based on molecular absorption line measurements.

Maps of molecular emission and absorption have now shown at least a partial view of many of the stages of the inflow and circulation of bar material, from individual uptake events well outside the center through the bar dust lanes into and within the nuclear star-forming ring. Our unparalleled viewpoint within the galactic disk and near the ring midplane provides a unique, if often bewildering perspective; all that remains is to take advantage of it.

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Appendix A: MSX bands

The MSX bands and wavelengths are enumerated in Table 1 of the text. Figure A.1 shows how these bands overlap the extinction curves for galactic dust with \( R_V = 3.1 \) and 5.5 [Weingartner & Draine (2001)].
Appendix B: Recombination Line Velocities

19-GHz H70α recombination line profiles drawn from the work of Liszt (1992) are shown in Fig. B.1.

Appendix C: N10: An exemplary H II region bubble

N10, at a kinematic distance of 4.9 kpc is one of three exemplary H II region bubbles recently discussed by Watson et al. (2008). Its resemblance to Sgr C is obvious.

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Fig. C.1. MSX and MAGPIS 20cm images of N10. Upper left: MSX A band. Lower left: MAGPIS 20cm image [Helfand et al. 2006]. Upper right: contours of 20cm radiocontinuum emission overlaid on the MSX A band image. Lower left: same for MSX E band. See also Watson et al. (2008).

Fig. A.1. Extinction cross-section per H-particle for galactic dust with RV = 3.1 and RV = 5.5 from Weingartner & Draine (2001).
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