COSMIC-RAY HEATING OF MOLECULAR GAS IN THE NUCLEAR DISK: LOW STAR FORMATION EFFICIENCY

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ABSTRACT

Understanding the processes occurring in the nuclear disk of our Galaxy is interesting in its own right, as part of the Milky Way, but also because it is the closest galactic nucleus. It has been more than two decades since the general phenomenon of higher gas temperature in the inner few hundred parsecs by comparison with local clouds in the disk of the Galaxy was recognized. This is one of the least understood characteristics of giant molecular clouds having a much higher gas temperature than dust temperature in the inner few degrees of the Galactic center. We propose that an enhanced flux of cosmic-ray electrons, as evidenced recently by a number of studies, is responsible for directly heating the gas clouds in the nuclear disk, elevating the temperature of the Galactic center gas above the dust temperature in the inner few degrees of the Galactic center. In addition, we report the detection of nonthermal radio emission from Sgr B2 F based on low-frequency GMRT and VLA observations. The higher ionization fraction and thermal energy due to the impact of nonthermal electrons in star-forming sites have important implications in slowing down star formation in the nuclear disk of our Galaxy and nuclei of galaxies.

Subject headings: cosmic rays — Galaxy: center — ISM: clouds — ISM: general — radio continuum: ISM — stars: formation

1. INTRODUCTION

The nuclear disk of our Galaxy has been studied extensively in molecular lines at millimeter wavelengths. Multitransition ammonia observations have probed the temperature of gas (Güsten et al. 1981, 1985; Morris et al. 1983; Serabyn & Güsten 1986; Hüttemeister et al. 1993), which was measured to be in the range of 50–120 K and was found to be uniformly high throughout the inner 500 pc of the Galaxy. A high spatial resolution study of 36 clouds between l = −1° and 3° (Hüttemeister et al. 1993) found a two-temperature distribution, warm low-density gas [Tkin ≈ 200 K, n(H2) ≈ 104 cm−3] and cool dense cores [Tkin ≈ 25 K, n(H2) ≈ 105 cm−3]. In other studies, observations of rotational transitions of H2, as well H2; absorption lines toward Galactic center clouds suggest a large quantity of warm (T ≈ 150–250 K) gas (Rodriguez-Fernández et al. 2001; Oka et al. 2005).

Molecular gas with T ≳ 100 K in the Galactic disk is heated by collisions with grains that have been warmed by hot stars in star-forming regions. Thus, regions of high kinetic temperatures inferred in NH observations of star-forming regions are strongly correlated with high dust temperature of clouds that accompany IR sources. However, the high gas temperature in giant molecular clouds (GMCs) in the nuclear disk (Lis et al. 2001) is inconsistent with the dust temperature, 18–22 K, inferred toward the inner 2° × 1° of the Galaxy from Submillimeter Common-User Bolometric Array 850 and 450 μm and Infrared Astronomical Satellite observations (Pierce-Price et al. 2000).

A global heating mechanism is needed to explain the significantly higher gas temperature than dust temperature in a large fraction of gas and dust clouds in the nuclear disk. With the exception of Sgr B2, the lack of embedded sources able to provide significant heating is supported by the paucity of 6.7 MHz methanol sources in this region (Caswell 1996). High ionization by a large flux of cosmic rays heating Galactic center molecular clouds has been suggested by a number of authors (Güsten et al. 1981; Hüttemeister et al. 1993). Alternative suggestions such as cloud collisions or global fast shocks have also been made, but there is no clear observational evidence to support these hypotheses (Martin-Pintado et al. 1997; Lis et al. 2001). Here we describe several recent studies indicating an excess cosmic-ray flux in the central region of the Galaxy and revisit the cosmic-ray heating scenario initially proposed by Güsten et al. (1981).

We also report the detection of nonthermal radio emission from the massive star-forming region Sgr B2 followed by the implications of cosmic-ray interaction with molecular clouds. In particular, the consequences of such interaction is discussed in the context of star formation in the Galactic center region.

2. EVIDENCE FOR ENHANCED COSMIC-RAY FLUX

Our interest in reconsidering the global heating of molecular clouds by cosmic rays in the central 500 pc stem from three different studies that indicate enhanced cosmic rays there. First, the fluorescent 6.4 keV Kα line iron emission from the Galactic center 0.08 molecular cloud, which lies ~15 pc in projection from the Galactic center (Tsuboi et al. 1997; Oka et al. 2001), is accounted for by the impact of low-energy cosmic-ray electrons (Yusef-Zadeh et al. 2002). The energy density over the 106 M⊙ cloud was estimated to be 1–2 eV cm−3, increasing to 150 eV cm−3 at the edge of the cloud where there it interacts with a nonthermal radio filament. The required energy density of cosmic rays at the edge of the cloud increases to ~250 eV cm−3 if the molecular mass of 0.01–0.08 M⊙ is 6 × 105 M⊙ (Handa et al. 2006). This idea was also applied to other prominent Galactic center molecular clouds from which diffuse 6.4 keV line emission is detected (Yusef-Zadeh et al. 2007). The energy density of the cosmic rays required to explain the observed X-ray emission from the clouds in the inner 2° × 0.5° of the Galaxy ranges between 20 and 10 eV cm−3. A cosmic-ray energy density of 0.2 eV cm−3 is required to explain the Galactic ridge X-ray emission (Valinia et al. 2000). The inferred ionization rates of the Galactic center clouds based on the 6.4 keV line measurements range between 2 × 10−14 and 5 × 10−13 s−1 H−1 (Yusef-Zadeh et al. 2002, 2007). Second, strong H3+ absorption along several lines of sight toward the Galactic center has been reported by Oka et al. (2005), who...
inferred that the ionization rate in this unique environment is in the range \((2-7) \times 10^{-15} \, \text{s}^{-1}\). Furthermore, an \(\text{H}_2\) study toward Sgr B2, one of the densest clouds in the Galaxy, implied also an ionization rate of \(-4 \times 10^{-16} \, \text{s}^{-1}\) (van der Tak et al. 2006). Third, the detection of low-frequency 74 MHz radio emission from the central disk of the Galaxy indicates enhanced cosmic rays from the central degree of the Galaxy. LaRosa et al. (2005) estimate the central disk of the Galaxy indicates enhanced cosmic rays from the central degree of the Galaxy. LaRosa et al. (2005) estimate that the cosmic-ray electron density of the central \(1.5^\circ \times 0.5^\circ\) is \(-7.2 \, \text{eV cm}^{-3}\), about 15 times higher than that in the local interstellar medium (ISM; Webber 1998). In addition, detailed spectral index measurements of extended radio sources show that 85% \pm 4% of 6 cm continuum emission corresponding to a flux density of 841 \pm 44 Jy from the inner \(-2.5^\circ \times 1^\circ\) of the Galaxy is nonthermal (Law 2007).

3. GMRT AND VLA RADIO CONTINUUM ANALYSIS

Motivated by the strong detection of 6.4 keV line emission from Sgr B2, we searched for evidence of nonthermal continuum emission from this cloud. To examine the picture of cosmic rays impacting molecular gas in Sgr B2, observations were conducted on 2003 March 14 using the Giant Meterwave Radio Telescope (GMRT) at 255 and 583 MHz with an effective bandwidth of 6 MHz using the default spectral line mode of the correlator. The field center was set at \(\alpha, \delta (J2000.0) = 17^\text{h} 46^\text{m} 00^\text{s}, -28^\circ 57' 00''\). 3C 48 was used as primary flux density calibrator, and 1830–36 was used as secondary calibrator. The data were processed using standard programs in AIPS. After calibration and editing of the 255 MHz data, a pseudocontinuum database of nine frequency channels was made from the central 5.6 MHz of the observed 6 MHz band. Images of the fields were formed after the application of phase self-calibration. In addition, we used archival data taken with the Very Large Array of the National Radio Astronomy Observatory4 at 1.4 GHz and 327 MHz. The data reduction is described in Yusef-Zadeh et al. (2004) and Nord et al. (2004), respectively.

Figure 1 (left) shows contours of 255 MHz radio continuum emission superimposed on a gray-scale image of the F source in Sgr B2 at 327 MHz. The peak emission at 327 MHz centered at \(\alpha, \delta (J2000.0) = 17^\text{h} 47^\text{m} 20^\text{s}, -28^\circ 23' 03''\) coincides with the position of the brightest cluster of 20 ultracompact H \(\Pi\) regions known as the F cluster in Sgr B2 Main (DePree et al. 1998). To determine the flux density of this source at 1.4 GHz and 255 MHz, we used Gaussian-fitted fluxes from background-subtracted images. The high-frequency emission from the spectrum of Sgr B2, as shown in Figure 1 (right), is due to bright, compact, and optically thick H \(\Pi\) regions whose flux densities should drop with decreasing frequencies. Increased free-free absorption by foreground material is responsible for the drop in the flux density at low frequencies. Despite the complexity of bright radio emission from Sgr B2, there is evidence for nonthermal emission at low frequencies. First, it is clear that the isolated emission from the F cluster dominates this complex region at low frequencies but has similar surface brightness to Sgr B2 North at high frequencies. The 1490 MHz images of Sgr B2 M and N show peak flux densities of \(-1.1 \, \text{Jy}\) within a beam size of \(10'' \times 10''\) (Yusef-Zadeh et al. 2004). Second, the spectral index \(\alpha\), where \(\nu F_\nu \propto \nu^{\alpha}\), between 255 and 327 MHz is estimated to be \(-1.28 \pm 0.4\), whereas \(\alpha\) is \(2.35 \pm 0.30\) between 1490 and 583 MHz. A flatter spectral index suggests a steep spectrum.

\(^4\) The National Radio Astronomy Observatory is a facility of the National Science Foundation, operated under a cooperative agreement by Associated Universities, Inc.
O and B stars in a radius of 0.04 pc, is reminiscent of another young, dense stellar cluster, G0.121+0.017 (i.e., the Arches cluster), from which nonthermal radio emission was recently reported (Yusef-Zadeh et al. 2003). A more detailed account will be given elsewhere.

To estimate the energy density of electrons, we adopt a typical nonthermal flux of 80 mJy at 255 MHz in a 22.5° × 16.8° beam, with a ν−2.5 spectrum. The relativistic electrons responsible for the emission must have an $E^{-2.5}$ energy spectrum, and we suppose that this extends down to 1 MeV. Their energy density is $\sim$3 eV cm$^{-3}$ for $B = 1$ mG or $\sim$150 eV cm$^{-3}$ for $B = 0.1$ mG. The corresponding ionization rate can be estimated by noting that in the MeV range the stopping power of the ISM is about 3.5 MeV g$^{-1}$ cm$^{-2}$ (ICRU 1984) and that on average one ionization occurs for each 40.1 eV deposited into the gas (Dalgarno et al. 1999). This yields an ionization rate $\sim$2 × 10$^{-14}$ s$^{-1}$ H$^{-1}$. The energy density and ionization rate are reduced by a factor of $\sim$25 if the electron spectrum only extends down to 10 MeV instead of 1 MeV.

4. EFFECTS OF ENHANCED COSMIC-RAY FLUXES IN STAR-FORMING REGIONS

High cosmic-ray fluxes in molecular clouds affect star formation by heating the gas and increasing its ionization fraction. Higher cloud temperatures increase the Jeans mass, potentially changing the initial mass function (IMF), while high ionization increases magnetic coupling to the cloud material, reducing ambipolar diffusion and increasing the time taken for gravitationally unstable cores to contract to the point that they overwhelm their magnetic support.

The heating associated with cosmic-ray ionizations can be estimated as follows. Each ionization of a hydrogen molecule is associated on average with 40.1 eV energy loss by electrons, of which 11% ends up as heat (e.g., Dalgarno et al. 1999). In addition, another 8 eV appears as heat when H$_2$ recomines (e.g., Maloney et al. 1996). Thus, each ionization of a hydrogen molecule is associated with the deposition of 12.4 eV of heat into the gas. As the ionization rate per hydrogen nucleus is half the H$_2$ ionization rate $\tilde{\gamma}_{H_2}$, the heating rate per hydrogen nucleus $\geq \Gamma/n_H \approx 25$ eV $\times \tilde{\gamma}_{H_2}$, or

$$\geq \Gamma/n_H = 4.0 \times 10^{-26} \frac{\tilde{\gamma}_{H_2}}{10^{-15} \text{ s}^{-1} \text{ H}^{-1}} \text{ ergs s}^{-1} \text{ H}^{-1}. \quad (1)$$

As pointed out by Güsten et al. (1981), an ionization rate $\tilde{\gamma}_{H_2} \sim 1 \times 10^{-15}$ s$^{-1}$ is sufficient to explain the observed gas temperature of $\sim$70 K (Goldsmith & Langer 1978). Using the cooling rates calculated by Neufeld et al. (1995) for $n$(H$_2$) = 5000 cm$^{-3}$ and $N$(H$_2$)/$\Delta v = 10^{-22}$ cm$^{-2}$ km$^{-1}$ s, the equilibrium temperatures are approximately 60, 130, and 280 K for $\tilde{\gamma}_{H_2} = 10^{-15}$, 10$^{-14}$, and 10$^{-13}$ s$^{-1}$ H$^{-1}$, respectively.

The Jeans mass can be estimated by equating the free-fall time of a uniform cloud core of density $\rho$ and radius $R$, i.e., $t_{ff} = 1/(Gp)^{1/2}$, to the sound crossing time $R/c_s$, yielding

$$M_J \approx 11 \left( \frac{T}{75 \text{ K}} \right)^{1/2} \left( \frac{n_H}{10^6 \text{ cm}^{-3}} \right)^{-1/2} M_\odot. \quad (2)$$

Collapse of this Jeans-unstable core is halted by the cloud’s magnetic field if the mass-to-flux ratio is less than the critical value $1/(4\pi G)^{1/2}$, i.e., if $B \geq 0.1n_H/(10^6 \text{ cm}^{-3})$ mG. However, the magnetic support is temporary because the cloud is weakly ionized, and the predominant neutral species are able to drift toward the center under the action of gravity while colliding with the ions and electrons that are tied to and supported by the near-static field lines. The neutral drift speed is determined by the balance between gravity and the drag due to collisions with the ions:

$$\frac{GM_p}{R^2} \approx n_e(\langle v \rangle)\rho v_d, \quad (3)$$

where $\langle v \rangle \approx 2 \times 10^{-9}$ cm$^{-3}$ s$^{-1}$ is the rate coefficient for ion-neutral momentum transfer. This yields a drift speed of a few hundredths of a kilometer per second. This drift increases the mass-to-flux ratio at the core’s center on a timescale $t_{AD} = R/v_d \approx 0.8 (x/10^{-4})$ Myr until it attains the critical value at which point dynamical collapse occurs on a few free-fall times. A more accurate calculation by Mouschovias (1987) reduces this estimate by a factor of 2. The ambipolar diffusion timescale is of order a few megayears for the standard interstellar ionization rates but is directly proportional to the ionization fraction, or equivalently to the square root of the ionization rate. Therefore, the timescale to achieve a supercritical core becomes large if the ionization rate is increased 100-fold over standard values.

Recent observations indicate that massive star formation has signatures similar to those seen in low-mass star formation: low star formation efficiency (Krumholz & Tan 2007), disk accretion (e.g., Cesaroni et al. 2005), and molecular outflows (e.g., Zhang et al. 2005). If the initial phases of high-mass star formation are analogous to low-mass star formation, then the formation of high-mass stars should be affected by the increased cosmic-ray ionization rate. Due to the higher Jeans mass in the warm gas, more massive stars are expected to preferentially form in the nuclear disk. This scenario is consistent with recent observations of a number of unique and young massive stellar clusters with a top-heavy IMF (Figer et al. 2004; Stolte et al. 2005; Nayakshin & Sunyaev 2005).

In this environment, the strong tidal shear will allow only the densest clouds to survive. Survival against shear requires that the gravitational frequency of the cloud, $(Gp)^{1/2}$, must exceed the orbital frequency around the Galactic center, $v/R$. Adopting a galactocentric distance $R = 100$ pc and an orbital speed $v = 150$ km s$^{-1}$, we find that clouds are tidally stable only if $n_H > 1.5 \times 10^5$ cm$^{-3}$.

The mass of the molecular nuclear disk is estimated to be $(2–6) \times 10^7 M_\odot$ (Oka et al. 1998; Pierce-Price et al. 2000) with typical gas temperature $\sim$70 K, so the cosmic-ray heating in this region totals $(2–6) \times 10^7$ ergs s$^{-1}$. The total cosmic-ray energy losses are 5 times higher, i.e., $(1–3) \times 10^8$ ergs s$^{-1}$. Assuming that $10^8$ ergs (10% of the energy of a typical supernova) goes into particles and the magnetic field (Duric et al. 1995) leads to one supernova per 10$^7$ yr. Given the high-density molecular gas in the nuclear disk, a supernova remnant (SNR) lifetime of $\sim 2 \times 10^9$ yr implies a few SNRs in the nuclear disk, comparable to the number of known SNRs (Gray 1994). The uniformity of the dense molecular gas distributed in the nuclear disk is inferred from the fact that $\sim 60\%$ of all known remnants in this region interact with molecular gas versus a value of $\sim 10\%$ in the Galactic disk. Assuming a Miller-Scalo IMF, the above estimate of the SN rate implies a star formation rate $>5 M_\odot$ yr$^{-1}$ (e.g., Condon 1992). Given that $\sim 5\%$

5 See Le Petit et al. (2004) and references therein for recent determinations of the ionization rate in diffuse clouds.
of the molecular gas in the Galaxy resides in the nuclear disk, the estimated star formation activity per unit mass, as traced by SN rate, is 2 orders of magnitude lower than that in the Galactic disk. Thus, star formation is fairly inefficient in this region of the Galaxy. Fatuzzo et al. (2006) also suggest that the increased ionization resulting from the interaction of SNRs with molecular clouds acts to suppress star formation.

Increased ionization due to enhanced cosmic rays is responsible for the lower efficiency of star formation in the Galactic nuclear disk than in the Galactic disk. Sgr B2 is the best example of current massive star formation in the nuclear disk, but even there the star formation per unit mass in Sgr B2 is an order of magnitude lower than that in W49 and W51, massive star-forming regions in the main spiral arms of the Galaxy (Gordon et al. 1993). All other massive clouds in the nuclear disk show even lower efficiency of star formation than in Sgr B2. For example, the GMC G0.25+0.01 has a star formation efficiency of 0.1%, roughly 30 times less than that in the disk of the Galaxy (Lis et al. 2001). The lack of numerous H₂O and methanol masers usually associated with early phases of star formation, especially in light of the large reservoir of warm and dense molecular clouds in this region, also indicates that the overall star formation rate in the molecular nuclear disk is generally low.

In conclusion, we have presented the evidence of cosmic rays in Sgr B2, arguably the most massive star-forming region in the Galaxy. We have also outlined a simple picture of the heating of molecular gas by cosmic rays and how its consequent high ionization fraction can delay the formation of stars and suppress the formation of low-mass stars in a high-pressure environment. The impact of the relativistic component of the ISM with molecular clouds has important implications for the mode of star formation and also the type of energetic activity found in nuclei of galaxies. A recent CO(7–6) line observation of NGC 253 (Bradford et al. 2003) also supports a picture in which cosmic rays are responsible for heating the molecular gas in the nucleus of this starburst galaxy.

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