ON THE TEMPERATURE STRUCTURE OF THE GALACTIC CENTER CLOUD G0.253+0.016

PAUL C. CLARK\textsuperscript{1}, SIMON C. O. GLOVER\textsuperscript{1}, SARAH E. RAGAN\textsuperscript{2}, RAHUL SHETTY\textsuperscript{1}, AND RAFAL S. KLESSEN\textsuperscript{1}

\textsuperscript{1}Zentrum für Astronomie, Institut für Theoretische Astrophysik, Universität Heidelberg, Albert-Ueberle-Str. 2, D-69120 Heidelberg, Germany; p.clark@uni-heidelberg.de, glover@uni-heidelberg.de, r.shetty@uni-heidelberg.de, klessen@uni-heidelberg.de
\textsuperscript{2}Max Planck Institut für Astronomie, Königstuhl 17, D-69117 Heidelberg, Germany; ragan@mpia.de

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ABSTRACT

We present a series of smoothed particle hydrodynamical models of G0.253+0.016 (also known as “The Brick”), a very dense molecular cloud that lies close to the Galactic center. We explore how its gas and dust temperatures react as we vary the strength of both the interstellar radiation field (ISRF) and the cosmic-ray ionization rate (CRIR). The cloud has an extent in the plane of the sky of roughly 3.4 pc × 9.4 pc. As its size along the line of sight is unknown, we consider two cases. In our fiducial, high-density model, we adopt a depth along the line of sight of 3.4 pc, and in the low-density model we assume an extent along the line of sight of 17 pc. To recover the observed gas and dust temperatures, we find that the ISRF must be around 1000 times the solar neighborhood value, and the CRIR must be roughly \( 10^{-14} \) s\(^{-1} \), regardless of the geometries studied. For such high values of the CRIR, we find that cooling in the cloud’s interior is dominated by neutral oxygen, in contrast to standard molecular clouds, which at the same densities are mainly cooled via CO. Our results suggest that the conditions near G0.253+0.016 are more extreme than those generally accepted for the inner 500 pc of the galaxy.

Key words: cosmic rays – evolution – Galaxy: center – ISM: molecules

Online-only material: color figures

1. INTRODUCTION

The environmental conditions in the Galactic center (GC) provide an extreme test of our current understanding of the star formation process (e.g., Papadopoulos 2010; Krumholz et al. 2012; Longmore et al. 2013; Kruijssen et al. 2013). With both stronger background radiation fields and higher cosmic-ray (CR) fluxes compared to clouds in the solar neighborhood, star formation is predicted to occur at higher volume and column densities than is typical in a standard giant molecular cloud (Elmegreen et al. 2008).

One notable example is G0.253+0.016 (also referred to as the “The Brick”), which displays both extremely high column and volume densities, yet very little sign of star formation (Güsten et al. 1981; Lis et al. 1994; Longmore et al. 2012). Despite the current lack of star formation, the physical conditions in this object are thought to be similar to those required for the formation of massive stellar clusters (Longmore et al. 2012).

In this Letter, we investigate the influence of the extreme GC environment on the thermodynamics of dense and massive molecular clouds, in an attempt to better understand the initial conditions for star formation in the inner molecular zone. We adopt values for the interstellar radiation field (ISRF) and the cosmic-ray ionization rate (CRIR) that are significantly higher than those measured in solar neighborhood molecular clouds. For more fundamental parameters such as the mass, dimensions, and turbulent velocity dispersion of the clouds, we take the values for G0.253+0.016 reported by Longmore et al. (2012). In contrast to the other clouds in the GC, the apparent lack of star formation in G0.253+0.016 makes it an ideal candidate for studying the effects of the environmental conditions on the thermal balance of the cloud.

2. COMPUTATIONAL METHOD

We perform our simulations using the smoothed particle hydrodynamics (SPH) code GADGET2 (Springel 2005). We have modified the code to include time-dependent chemistry and a treatment of the main heating and cooling processes (described below). We have also included an implementation of the TreeCol algorithm (Clark et al. 2012) to obtain column density maps of the sky as seen by each SPH particle. These maps (including total, H2 and CO column densities) are used to calculate the influence of the ISRF on the gas and the dust.

We assume for simplicity that the spectral shape of the ISRF follows Draine (1978) in the UV and Black (1994) at longer wavelengths. We denote the solar neighborhood value of the strength of the ISRF as \( G_0 \), and perform simulations with field strengths 100 \( G_0 \) and 1000 \( G_0 \) (see Table 1). Note that this multiplicative scaling is done equally at all wavelengths. For our dust model, we use a combination of values from Ossenkopf & Henning (1994; non-coagulated, thick ice mantles grains) for wavelengths longer than 1 μm, and from Mathis et al. (1983) at shorter wavelengths. To compute the visual extinction, we use the relationship \( A_V = 5.348 \times 10^{-22} (N_{H,\text{tot}} / 1 \text{ cm}^{-2}) \), where \( N_{H,\text{tot}} \) is the total hydrogen column density (Bohlin et al. 1978; Draine & Bertoldi 1996). For simplicity, we do not account for any changes in the extinction curve that may occur due to dust coagulation. For the CRIR, we adopt a value of \( I_{\text{CR,0}} = 3 \times 10^{-17} \text{s}^{-1} \) as our solar neighborhood value (van der Tak & van Dishoeck 2000), and assume that each ionization event deposits 20 eV of energy into the gas (Goldsmith & Langer 1978). The dependence of the CRIR on column density is highly uncertain (Padovani et al. 2009), and we assume for simplicity that no attenuation occurs. We do not include the effects of ionization by hard X-rays, as this does not appear to be a major heat source in the GC, given the relatively low X-ray luminosity (Rodríguez-Fernández et al. 2004; Schleicher et al. 2010).

For the chemistry we adopt the reduced CO network of Nelson & Langer (1999). Details can be found in Glover & Clark (2012b), and a description of how the chemistry interacts with the ISRF via the TreeCol algorithm is given in Glover & Clark (2012a).

3. INITIAL CONDITIONS AND MODEL PARAMETERS

For the initial conditions in this study, we take the cloud properties derived in Longmore et al. (2012) for G0.253+0.016...

Table 1  
Summary of the Simulations

<table>
<thead>
<tr>
<th>Model</th>
<th>$L_x$ (pc)</th>
<th>$L_y$ (pc)</th>
<th>$L_z$ (pc)</th>
<th>$\Sigma_{\text{min,0}}$ (cm$^{-2}$)</th>
<th>$n_0$ (cm$^{-3}$)</th>
<th>$I_{\text{ISRF}}$ (G0)</th>
<th>$I_{\text{CR}}$ (s$^{-1}$)</th>
<th>$x$(H$_2$)</th>
<th>$x$(CO)</th>
<th>$x$(C*)</th>
<th>$x$(O)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>9.4</td>
<td>3.4</td>
<td>3.4</td>
<td>$3.6 \times 10^{23}$</td>
<td>$3.5 \times 10^4$</td>
<td>$1000$</td>
<td>$3 \times 10^{-14}$</td>
<td>0.477</td>
<td>1.5 $\times 10^{-5}$</td>
<td>1.33 $\times 10^{-5}$</td>
<td>3.06 $\times 10^{-4}$</td>
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<tr>
<td>2</td>
<td>9.4</td>
<td>3.4</td>
<td>3.4</td>
<td>$3.6 \times 10^{23}$</td>
<td>$3.5 \times 10^4$</td>
<td>$1000$</td>
<td>$3 \times 10^{-15}$</td>
<td>0.500</td>
<td>9.59 $\times 10^{-5}$</td>
<td>8.02 $\times 10^{-6}$</td>
<td>2.24 $\times 10^{-4}$</td>
</tr>
<tr>
<td>3</td>
<td>9.4</td>
<td>3.4</td>
<td>3.4</td>
<td>$3.6 \times 10^{23}$</td>
<td>$3.5 \times 10^4$</td>
<td>$1000$</td>
<td>$3 \times 10^{-16}$</td>
<td>0.500</td>
<td>1.11 $\times 10^{-4}$</td>
<td>3.08 $\times 10^{-6}$</td>
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</tr>
<tr>
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<td>3.4</td>
<td>17.0</td>
<td>$7.3 \times 10^{22}$</td>
<td>$6.7 \times 10^3$</td>
<td>$100$</td>
<td>$3 \times 10^{-16}$</td>
<td>0.500</td>
<td>6.65 $\times 10^{-5}$</td>
<td>1.76 $\times 10^{-5}$</td>
<td>2.53 $\times 10^{-4}$</td>
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<tr>
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<td>3.4</td>
<td>17.0</td>
<td>$7.3 \times 10^{22}$</td>
<td>$6.7 \times 10^3$</td>
<td>$100$</td>
<td>$3 \times 10^{-15}$</td>
<td>0.496</td>
<td>2.62 $\times 10^{-5}$</td>
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<tr>
<td>6</td>
<td>9.4</td>
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<td>17.0</td>
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<td>$6.7 \times 10^3$</td>
<td>$100$</td>
<td>$3 \times 10^{-16}$</td>
<td>0.497</td>
<td>6.10 $\times 10^{-5}$</td>
<td>2.52 $\times 10^{-5}$</td>
<td>2.59 $\times 10^{-4}$</td>
</tr>
</tbody>
</table>

Notes. Columns 2–4: initial physical dimensions of the cloud. Column 5: minimum column density, measured along the shortest axis. Column 6: initial hydrogen nuclei number density. Column 7: strength of the interstellar radiation field, in units of the local value. Column 8: cosmic-ray ionization rate. Columns 9–12: final average kinetic temperatures of $\sim$80 K (Wainsley & Ungerechts 1983). A recent formaldehyde survey (Ao et al. 2013) finds average kinetic temperatures of $65$–$70$ K, which agrees within the uncertainties. However, observations of high-excitation ammonia lines suggest that G0.253+0.016 has a complex gas temperature structure, with components up to 400 K, that has yet to be modeled (E. Mills, 2013, private communication). What environmental conditions are required to produce such temperatures?

The typical features of our cloud are illustrated in Figure 1, which shows the column densities of one of the clouds in the $x$–$y$ plane (i.e., integrating along $z$), and the accompanying mean gas and dust temperature maps. This cloud is our most extreme case studied, with $I_{\text{ISRF}} = 1000G_0$, $I_{\text{CR}} = 1000I_{\text{CR,0}}$, and our “fiducial” cloud geometry. However, the features of this cloud are mirrored in our other simulations—the clouds have a hot skin and a relatively cool interior, and are highly structured by the supersonic turbulence. The images in Figure 1 are taken just as the first collapsing core exceeds a density of around $10^8$ cm$^{-3}$, and so represent the state of the cloud at the onset of star formation. All the other clouds in this study will be presented at the same point in their evolution.

In Figure 2, we show the gas and dust temperatures in the clouds as a function of the position along the $x$-axis. The most obvious feature of these profiles is that the gas and dust have different temperatures throughout the cloud. They are not thermodynamically coupled on the scales shown here, consistent with the observations mentioned above.

The profiles also reveal how the environment affects the cloud temperature. We see that the CRs are responsible for heating the gas, while the ISRF is primarily responsible for heating the dust. Such a result is expected. The high column density of this cloud means that photoelectric emission in the cloud interior is strongly suppressed, as the UV photons responsible for it are readily absorbed near the surface of the cloud. As such, the ISRF can play only a minor role in directly heating the gas. On the other hand, as the CRs have no attenuation in our model, they are free to heat the cloud’s gaseous interior throughout. The ISRF can, however, heat the dust at the center of the cloud, as this heating comes primarily from longer wavelength photons, which are able to penetrate much further than the UV photons. In summary, for clouds with such an extreme column density as G0.253+0.016, the heating of the dust and gas is effectively split into two components.

Our 3D modeling results suggest that for our fiducial cloud model, the environmental parameters that best reproduce the observed temperatures are $I_{\text{ISRF}} = 1000$ $G_0$ and $I_{\text{CR}} = 1000I_{\text{CR,0}}$. These are quoted with respect to the number of $H$ nuclei. A fully molecular gas therefore has $x$(H$_2$) = 0.5. The total carbon and oxygen abundances in the models are $1.4 \times 10^{-4}$ and $3.2 \times 10^{-4}$, respectively.
Figure 1. Column density, and mean gas and dust temperatures in our fiducial cloud setup (simulation “1” in Table 1), with the ISRF set at 1000 $G_0$ and the CRIR at $3 \times 10^{-14} \text{s}^{-1}$.

(A color version of this figure is available in the online journal.)

$I_{\text{CR}} = 1000 I_{\text{CR,0}}$. Reducing either of these values by a factor of 10 results in gas or dust temperatures that are too low to agree with the observations.

One potential source of error is simply that we have underestimated the extent of G0.253+0.016 along the observed line of sight, and so the true effective column of the cloud is much smaller than we are assuming in the fiducial models. However, we find that similar environmental conditions are also required when we consider our lower-density version of G0.253+0.016. These models are shown on the bottom row of Figure 2. Even in these lower column density clouds, we see that the ISRF is mainly responsible for determining the dust temperatures (i.e., there is very little gas–dust thermodynamic coupling), and the CRIR is mainly responsible for determining the gas temperatures. Our dust temperatures are now a little higher than the observed values throughout the cloud, suggesting that for this geometry the $I_{\text{ISRF}}$ would need to be lower than 1000 $G_0$. However, we see that by 100 $G_0$ the ISRF is already too low to explain the observed temperatures. Also, we see that $I_{\text{CR}} = 100 I_{\text{CR,0}}$ results in a gas temperature of around 30 K in the interior of the cloud—again, this is inconsistent with the observations.

Figure 2 also shows that the geometry of the cloud affects the temperature gradients along the cloud. This is particularly evident when one looks at the gas temperature, especially when $I_{\text{ISRF}}$ is high (see, e.g., the bottom right panel). This implies that it should be possible to constrain both the total ISRF and the cloud’s geometry by fitting the gradient of the gas temperature in the cloud modeling. Such a study is worth revisiting, once maps of the gas temperature with sub-parsec resolution become available.

Finally, we note that both the gas and dust temperatures can vary considerably along a line of sight from the averages shown...
in Figure 2. This can already be seen in the images in Figure 1. However, we also show in Figure 3 how the temperatures vary as a function of density in our fiducial case. We see that at high densities (>10^6 cm^{-3}), once the dust and gas thermally couple, the temperatures can be relatively cold.

5. HEATING AND COOLING PROCESSES

In this section we investigate the heating and cooling processes for the gas in more detail. The dominant processes that govern the gas temperature are shown as functions of density in Figure 4 for the two most extreme cases: our fiducial cloud (n_0 = 3.5 \times 10^4 cm^{-3}), with I_{ISRF} = 1000 G_0 and I_{CR} = 1000 I_{CR,0}, and one of the lower-density clouds (n_0 = 6.7 \times 10^3 cm^{-3}), with I_{ISRF} = 100 G_0 and I_{CR} = 10 I_{CR,0}.

In both clouds, the dominant heating processes follow a broadly similar pattern. At the lowest densities, which represent the outskirts of the clouds in these simulations, the dominant heat source is photoelectric emission from dust grains. This falls off sharply as we move to higher densities as a result of the increasing extinction as one moves into the cloud’s interior. At slightly higher densities, the heating caused by CRs starts to dominate the thermal balance. In the case of the hotter, denser cloud, this process remains the main heating source until we reach a number density n \approx 10^8 cm^{-3}, corresponding to our resolution limit. In the lower density cloud, embedded in the less extreme environment, shock heating becomes the main source of heat input to the gas at densities above n \approx 10^5 cm^{-3}. Note that since neither compression nor shock heating is dominant in the high CRIR case, the temperature of the cloud cannot be used to determine its age.

When we compare the main cooling processes, we also find some similarities. In the low-density outskirts, where the gas is warm and there is little CO, we find that C^{+} and neutral oxygen emission are the main coolants, as in the low-density interstellar medium. Given the high densities and temperatures of the cloud’s skin, and the fact that we start with the hydrogen in molecular form, we also find that H_2 can be an effective coolant at the outskirts.

As we move into the cloud, however, the gas temperature drops and the C^{+} recombines to form C and then CO. The identity of the dominant coolant therefore changes. In the low-density cloud, CO cooling dominates in this slightly denser...
CO + He⁺ → C⁺ + O + He.  

(1)
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REFERENCES