Star Formation at the Galactic Center

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ABSTRACT. Molecular clouds at the Galactic center (GC) have environments considerably different from their disk counterparts. The GC may therefore provide important clues about how the environment affects star formation. Interestingly, while the inner 50 pc of our Galaxy include a remarkable population of high-mass stars, the initial mass function (IMF) appears to be consistent with a Salpeter slope down to \( \sim 1 \, M_\odot \). We show here that the loss of turbulent pressure due to ambipolar diffusion and the damping of Alfvén and fast MHD waves can lead to the formation of dense condensations exceeding their Jeans limit. The fragmentation and subsequent collapse of these condensations is similar to the diffusion-driven protostellar collapse mechanism expected to occur within nearby “regular” molecular clouds. As such, a Salpeter IMF at the GC is not surprising, though the short dynamical timescales associated with the GC molecular clouds may help explain the lower star formation efficiency observed from this region.

1. INTRODUCTION

Basic star formation theory holds that a star’s initial mass is dependent, at least in part, on the environment in which it is born (Bonnell et al. 2007). It is quite reasonable therefore to expect that the initial mass function (IMF) may vary for different types of stellar populations. Yet the IMF appears to be quite uniform throughout our galaxy (Kroupa 2002; Massey 2003), being well described by a power-law form \( dN/dm \propto m^{-\alpha} \) for \( m > 1 \, M_\odot \) and a lognormal form below this value (Adams & Fatuzzo 1996; Kroupa 2001; Chabrier 2003). At present, there is only one known cluster in our Galaxy that appears to have a considerably top-heavy IMF—the Galactic center (GC) cluster. Two other clusters that lie within 50 pc in projection from the nucleus also contain a remarkable number of high-mass stars—the Quintuplet and the Arches clusters. The Quintuplet cluster contains more Wolf-Rayet stars than any other cluster in the galaxy. However, it is significantly more dispersed than the Arches cluster, and as such, its mass function has not been determined. In contrast to the Quintuplet, the Arches cluster is quite dense, containing at least 150 O stars within a radius of 0.6 pc. While the mass function for this cluster was initially thought to be considerably shallower than a Salpeter IMF (Stolte et al. 2005; Kim et al. 2006), the peculiarities in the Arches mass function can apparently be attributed to evolution, and the Arches initial mass function may well be consistent with a Salpeter slope down to \( \sim 1 \, M_\odot \) (Portegies Zwart et al. 2007).

These results are somewhat surprising given that the molecular clouds within \( \sim 100 \) pc of the GC have considerably different environments than their disk counterparts (e.g., Crocker et al. 2007). While a lot of progress has been made over the past decade in the field of star formation theory, a complete understanding of how a star acquires its initial mass remains elusive. At present, two different star formation paradigms are seemingly favored by the star formation community—the “standard” paradigm (Shu et al. 1987; see also more recent works by Adams & Shu 2007; Tassis & Mouschovias 2007; Kudoh & Basu 2008; Basu et al. 2009) and the turbulent fragmentation paradigm (Padoan & Nordlund 2002; Mac Low & Klessen 2004; Bonnell et al. 2007). On the observational front, a recent survey of magnetic field strengths in nearby dark cloud cores aimed at testing these scenarios failed to yield conclusive results (Troland & Crutcher 2008). The extreme molecular cloud environments at the GC (Yusef-Zadeh et al. 2000; Melia & Falcke 2001) may therefore provide an important test case from which to consider star formation theory. Indeed, recent observations now make it possible to consider certain aspects of star formation within the context of the standard paradigm.

For example, Yusef-Zadeh et al. (2007) have recently compiled evidence for an enhancement of cosmic-ray electrons within the Galactic center region, and claim that this enhancement may be responsible for heating the gas clouds to temperatures above the dust temperature. These authors note that higher cloud temperatures increase the Jeans mass, thereby accounting for what at the time was believed to be a top-heavy IMF at the...
GC (Stolte 2005; Kim et al. 2006). In addition, Yusef-Zadeh et al. (2007) suggest that the high ionization, which would increase magnetic coupling to the cloud material and lengthen the ambipolar diffusion time (Fatuzzo et al. 2006), could be responsible for the low star formation efficiency observed in this region (Gordon et al. 1993; Lis et al. 2001).

We extend this line of investigation by considering how the extreme environments associated with the dense cores of the GC molecular clouds impact star formation within those regions. Given the strengths of the magnetic fields which permeate this region, the critical mass below which cores can be supported against gravitational collapse is quite a bit higher in this region than in typical disk giant molecular clouds (GMCs). While the high ionization rates at the GC increase the coupling between the magnetic field and neutral gas, as noted by Yusef-Zadeh et al. (2007), the high densities of molecular gas in this region offsets the higher ionization rate’s effect on the ambipolar diffusion time, which scales as $\tau_{\text{AD}} \propto (\zeta/n)^{1/2}$. As a result, magnetic support can be effectively removed in the densest regions of the GC molecular clouds, consistent with the observation that the most active star formation regions in the nuclear disk, such as Sgr B2, are associated with a dense environment.

Interestingly, magnetic support within the dense regions of the GC molecular clouds can also be efficiently removed via strong damping of Alfvén and fast MHD waves, a process that has been proposed for removing part of the support against gravity and thereby initiating fragmentation (or core formation) in typical molecular clouds (Mouschovias 1987; Mouschovias & Psaltis 1995). A second important aspect of this work is the assessment of what impact this mechanism has on the loss of magnetic support in the GC molecular clouds. Specifically, while ambipolar diffusion acts to gradually remove magnetic support in massive dense cores, the reduction of magnetic pressure within the densest gas of the GC may result preferentially from MHD wave damping (Mouschovias 1991, Balsara 1996), which would then lead to the formation of dense condensations with masses that, depending on environmental conditions, can range between ~0.1 and 30 $M_\odot$. Although condensations whose masses exceed their Jeans limit may initially be supported against gravitational collapse by slow MHD waves, the relatively short ambipolar diffusion times associated with these objects (given their greater density over the surrounding medium) would efficiently remove the remaining magnetic pressure support.

### 2. IMPACT OF THE GC ENVIRONMENT ON STAR FORMATION

The molecular clouds near the GC have environments considerably different from their galactic disk counterparts. For example, the average molecular hydrogen number density ($n_{\text{H}_2}$) over the Sgr B complex—the largest molecular cloud complex (Lis & Goldsmith 1989, 1990; Paglione et al. 1998) near the GC—has a value of $3 \sim 10 \times 10^3$ cm$^{-3}$. Like its traditional counterparts, Sgr B displays a highly nonlinear structure, containing two bright subregions, Sgr B1 and Sgr B2; the latter has an average molecular density of $\sim 10^6$ cm$^{-3}$, and contains three dense ($n \sim 10^{7.3-8}$ cm$^{-3}$), small ($r \sim 0.1$ pc) cores—labeled North, Main, and South. These cores also show considerable structure, containing numerous ultracompact and hypercompact H II regions. As such, the densities associated with the GC molecular clouds are about 2 orders of magnitude greater than those in the disk of our galaxy.

In the simplest strong-magnetic field case (which is the focus of our study), flux freezing arguments imply that the magnetic field strength $B$ in the interstellar medium scales to the gas density as $B \propto n^{1/2}$. Indeed, an analysis of magnetic field strengths measured in molecular clouds by Crutcher (1999) yielded a relation between $B$ and $n$ of the form $B \propto n^{0.47}$, although there is a significant amount of scatter in the data used to produce this fit. Interestingly, one of the data points used in establishing this relation comes from observations of Sgr B2 (Crutcher 1996), for which $B_{\text{los}} = 0.5$ mG at a density of $n = 2.500$ cm$^{-3}$. This datum is an outlier to the rest of the data, being well above the established fitted scaling relation. A significantly better correlation to the data was obtained in a subsequent analysis by Basu (2000) who, including the effects of cloud flattening along the mean magnetic field direction, obtained the relation

$$B = \left(8\pi c_1\right)^{1/2} \frac{\sigma_v n^{1/2}}{\mu},$$

where $c_1 \approx 1$ is an undetermined proportionality constant between the mean mass density $\rho$ and the midplane mass density, $\sigma_v$ is the total one-dimensional velocity dispersion (related to the FWHM of spectral lines $\Delta V$ via the relation $\sigma_v = \Delta V/[8 \ln 2]^{1/2}$), and $\mu$ is the dimensionless mass-to-flux ratio in units of the critical value $(2\pi G^{1/2})^{-1}$ for a disk. The best least-squares fit was obtained for $\sqrt{c_1}/\mu = 0.8$, for which the Sgr B2 datum is no longer an outlier. This result agrees with the prediction of ambipolar diffusion-driven star formation, and is consistent with the idea that nonthermal line widths arise from MHD fluctuations for which the Alfvén Mach number is of order unity. Specifically, MHD waves would propagate through this medium with an Alfvén speed

$$v_a = \frac{B}{(4\pi \rho)^{1/2}} = 31 \text{ km s}^{-1} \left(\frac{B}{1 \text{ mG}}\right) \left(\frac{n}{2500 \text{ cm}^{-3}}\right)^{-1/2},$$

consistent with the interpretation that the observed 15–50 km s$^{-1}$ supersonic internal velocity dispersions (Morris & Serabyn 1996) result from magnetic turbulence.

The coupling between the magnetic field and the molecular gas depends sensitively on the ion fraction and, hence, on the local ionization rate. Several recent studies indicate an excess of cosmic-ray flux within the central region of the galaxy. For example, the ionization rate for Sgr B has been determined to be...
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The temperature structure in the GC molecular clouds is quite complicated, at least two kinetic temperatures, $T_{\text{kin}} \sim 200$ K and $T_{\text{kin}} \sim 25$ K, are indicated in each cloud, with evidence that the cooler gas is associated with higher densities (Hüttemeister et al. 1993b). Sgr B2 Main—with a temperature of $\sim 200$ K and density $\sim 2 \times 10^7$ cm$^{-3}$—appears to be an exception (Hüttemeister 1993a; De Vicente et al. 1996). We note, however, that this structure contains numerous ultracompact H II regions (de Pree et al. 1998), so the high temperatures may be due to the presence of massive stars.

In the “standard” star formation paradigm, dense cores are initially subcritical and thus supported by magnetic turbulence until ambipolar diffusion increases the mass to magnetic flux ratio sufficiently that collapse can ensue. This phase is then followed by an inside out collapse that leads to the formation of a central star. The characteristic ambipolar diffusion timescale under quasi-static, subcritical assumptions is $\tau_{\text{AD}} \approx \tau_{ff}/(\tau_{ni})$, where $\tau_{ff} = \sqrt{3\pi/(32G\rho)}$ and $\tau_{ni} \approx (3\sigma v n_i)^{-1}$ are, respectively, the free-fall time and the neutral-ion collision time (Mouschovias 1976; Shu 1983, 1992), and $\langle \sigma v \rangle n_i \approx 1.7 \times 10^{-9}$ cm$^{-3}$ s$^{-1}$ is the average collision rate between ions and neutrals (Mouschovias 1991). The ion density is well approximated by the relation

$$n_i = 3.2 \times 10^{-3} \text{ cm}^{-3} \left(\frac{n}{10^7 \text{ cm}^{-3}}\right)^{1/2} \left(\frac{\zeta}{\zeta_{\text{CR}}}\right)^{1/2},$$

where $\zeta_{\text{CR}} = 10^{-17}$ s$^{-1}$, so long as $\zeta/n > 10^{-22} - 10^{-24}$ cm$^3$ s$^{-1}$ (Elmegreen 1979). Given that $\zeta/n \sim 10^{-23}$ cm$^3$ s$^{-1}$ in the dense regions of the GC, we consider both the case that $n_1$ is given by equation (3) for all values of $n$ (Case I), and the case where this relation holds only for $n < n_{\text{crit}} = 10^6 (\zeta/\zeta_{\text{CR}})$ cm$^{-3}$, beyond which $n_1 = 10^{-2}(\zeta/\zeta_{\text{CR}})$ cm$^{-3}$ (Case II).

Correspondingly, the ambipolar diffusion time is given by the expressions

$$\tau_{\text{AD}} \approx 2.2 \text{ Myr} \left(\frac{\zeta}{\zeta_{\text{CR}}}\right)^{1/2} \left(\frac{n}{10^5 \text{ cm}^{-3}}\right)^{-1/2}$$

(4a)

for Case I and for Case II when $n < n_{\text{crit}}$; and

$$\tau_{\text{AD}} \approx 7.1 \text{ Myr} \left(\frac{\zeta}{\zeta_{\text{CR}}}\right) \left(\frac{n}{10^5 \text{ cm}^{-3}}\right)^{-1}$$

(4b)

for Case II when $n > n_{\text{crit}}$, in good agreement with results from more sophisticated analyses (Ciolek & Mouschovias 1995). As pointed out by numerous authors, this timescale is too slow, by a factor of $\sim 3$–10, to account for the observed statistics of starless molecular cores in typical molecular cloud environments (Jijina et al. 1999; see also Mouschovias et al. 2006). However, several mechanisms have recently been proposed which speed up the process (Ciolek & Basu 2001; Zweibel 2002; Fatuzzo & Adams 2002), thereby addressing one of the main criticisms of the “standard” paradigm.

Dense cores ($r \sim 0.1$ pc, $n \sim 5 \times 10^7$ cm$^{-3}$) within the GC molecular clouds contain several thousand solar masses of gas, well in excess of their Jeans limit. It would thus appear that magnetic turbulence is responsible for the global support of these regions. However, Alfvén and fast MHD waves can only couple to the neutral gas if the ion-neutral collision time is shorter than the MHD time. As a result, star formation can be initiated by the loss of turbulent support attributed to ambipolar diffusion damping of hydromagnetic waves (Mouschovias 1987). This loss of turbulent support occurs below a lengthscale

$$\lambda_{\alpha} \equiv \pi v_\alpha \tau_{ni} \approx 1.8 \times 10^{17} \left(\frac{v_\alpha}{31 \text{ km/s}}\right) \left(\frac{n}{10^7 \text{ cm}^{-3}}\right)^{-1/2} \left(\frac{\zeta}{\zeta_{\text{CR}}}\right)^{-1/2}$$

(5a)

for Case I and for Case II when $n < n_{\text{crit}}$; and

$$\lambda_{\alpha} \approx 5.7 \times 10^{17} \left(\frac{v_\alpha}{31 \text{ km/s}}\right) \left(\frac{\zeta}{\zeta_{\text{CR}}}\right)^{-1}$$

(5b)

for Case II when $n > n_{\text{crit}}$, such that magnetic disturbances with wavelengths $\lambda < \lambda_{\alpha}$ diffuse before collisions between the neutrals and ions have had time to transmit to the neutrals the magnetic force associated with the disturbance (Mouschovias 1991; Balsara 1996). Below this lengthscale, Alfvén and fast MHD waves become completely nonpropagating and are quickly damped.

For molecular clumps in typical GMCs ($n \approx 10^3$ cm$^{-3}$; $v_\alpha \approx 1$ km s$^{-1}$; $\zeta = \zeta_{\text{CR}}$), $\lambda_{\alpha} \approx 0.2$ pc, smaller than the typical clump size ($\sim 0.2$–2 pc) required for MHD waves to support these structures from collapse. The loss of magnetic support on scales less than $\lambda_{\alpha}$ is therefore expected to play a role in setting the lengthscales at which ambipolar diffusion becomes significant and fragmentation or core formation is initiated (Mouschovias 1987; 1991). In turn, there is a natural mass scale of $\sim 1 M_\odot$ associated with the ambipolar-driven star formation process. Indeed, massive clumps observed in typical GMCs are comprised of $\sim 100$–1000 small ($R \sim 0.1$–0.2 pc), dense ($\sim 10^4$–$10^5$ cm$^{-3}$) cores whose mass function has been measured to range from $\sim 1$–100 $M_\odot$ (with a peak $\sim 10 M_\odot$) by Jijina et al. (1999), and more recently, from $\sim 0.2$–20 $M_\odot$ (with a characteristic mass of $\sim 2 M_\odot$) by Lada et al. (2008). We note, however, that while the loss of magnetic support due to wave damping may serve to seed this structure, the evolutionary timescale for the collapse is still set by the ambipolar diffusion time rather than the free-fall time (Mouschovias & Psaltis 1995). Furthermore, structures in molecular clouds (e.g., cores) typically exhibit Bonnor-Ebert density profiles. That it, their
densities scale as $r^{-2}$ until flattening occurs at radii below $r_C \sim 10^{16}$ cm. As a result, $\lambda_0 \propto n^{-1/2} \propto r$, and remains smaller than the core size at a given density for all but the central (flattened) part of the cores.\footnote{Oishi and Mac Low (2006) find that ambipolar diffusion is unable to set a characteristic scale for gravitational collapse and star formation in turbulent molecular clouds, owing presumably to support from slow MHD waves. However, the simulations of Oishi and Mac Low (2006) were performed in the absence of gravity, the presence of which can lead to the damping of short wavelength slow MHD waves, albeit at rates about 2 orders of magnitude smaller than the damping rates for the fast MHD and Alfvén waves at the same wavelength (Balsara 1996).}

Estimating the corresponding length and mass scales in the dense regions of the GC is hampered by the significant uncertainty on the environmental conditions within this region, with $10 \leq \zeta/\zeta_{CR} \leq 40$, $10^7$ cm$^{-3} \leq n \leq 10^8$ cm$^{-3}$, and an uncertainty as to whether or not the relation between $n_i$ and $n$ given by equation (3) holds here. In addition, the density and magnetic field strengths are likely to fluctuate significantly within this region (indeed, in typical GMCs, $\delta B \sim B$). To keep the analysis as simple as possible, we plot in Figure 1 the mass of condensations ($M_C \approx \rho \lambda_C^3$) that will decouple from the magnetic field as a function of density for $\zeta/\zeta_{CR} = 10$ (solid curve), 20 (short dashed curve), and 40 (long dashed curve). The dotted curve shows the Jeans mass as a function of density for $T = 25$ K. In order to aid our analysis, we also plot the ambipolar diffusion time $\tau_{AD}$ as given by equation (4) in Figure 2. Note that the lower branch of each curve in Figure 1 corresponds to the case for which equation (3) holds for all densities, and the upper branch corresponds to the case where $n_i$ is constant above $n_{\text{crit}} = 10^6$ cm$^{-3}(\zeta/\zeta_{CR})$. Conversely, the upper branch of each curve in Figure 2 corresponds to the case for which equation (3) holds for all densities, and the lower branch corresponds to the case where $n_i$ is constant above $n_{\text{crit}}$.

Our results indicate that condensations which form in cool (25 K), dense regions of the GC molecular clouds would exceed their Jeans limit unless the ionization fraction is high ($\zeta \gtrsim 30\zeta_{CR}$) and the relation between $n_i$ and $n$ given by equation (3) holds throughout the core environment. Whether or not condensations in excess of their Jeans mass could be supported against gravitational collapse by slow MHD waves is beyond the scope of this article. We note, however, that even if this were the case, the greater densities of these condensations over the rest of the core (due to the partial loss of magnetic support) would then lead to lower ambipolar diffusion times, as can be seen in Figure 2. As such, support by slow MHD waves can at best delay the gravitational collapse of these massive condensations, meaning that the collapse timescale would then be set by the ambipolar diffusion time rather than the free-fall time.

Alternatively, if condensations form with masses below their Jeans limit, ambipolar diffusion would first need to remove the magnetic field globally from dense regions of the GC, a process that would take $\sim 0.1$–1 Myr. One would then expect these regions to fragment before collapse ensues. It is important to note that Figure 1 presents an “average” value of condensation mass expected to form in a region with density $n$. The presence of density and magnetic fluctuations expected within this highly dynamic region would almost certainly lead to the formation of a fairly wide distribution of condensation masses.

![Fig. 1.—Condensation mass as a function of density; the mass of condensations that form as a result of magnetic decoupling due to damping of Alfvén and fast MHD waves as a function of density for three different ionization rates: $10\zeta_{CR}$ (solid curve); $20\zeta_{CR}$ (short dashed curve); and $40\zeta_{CR}$ (long dashed curve). At densities above $n_{\text{crit}} = (\zeta/\zeta_{CR})10^6$ cm$^{-3}$, the lower branch of each curve corresponds to the case where $n_i$ is set through the scaling given by equation (3) for all $n$, and the upper branch corresponds to the case for which $n_i$ is assumed constant for densities above $n_{\text{crit}}$. The dotted curve indicates the Jeans mass as a function of density for $T = 25$ K.](Fig1.png)

![Fig. 2.—Ambipolar diffusion time as a function of density as given by equation (4) for three different ionization rates: $10\zeta_{CR}$ (solid curve); $20\zeta_{CR}$ (short dashed curve); and $40\zeta_{CR}$ (long dashed curve). At densities above $n_{\text{crit}} = (\zeta/\zeta_{CR})10^6$ cm$^{-3}$, the upper branch of each curve corresponds to the case where $n_i$ is set through the scaling given by equation (3) for all $n$, and the lower branch corresponds to the case for which $n_i$ is assumed constant for densities above $n_{\text{crit}}$.](Fig2.png)
This result may have important consequences for star formation theory. Specifically, while the molecular environment at the GC is extreme compared to local GMC environment, the relevant physical quantities associated with ambipolar diffusion-driven star formation (mainly, the flux to mass ratio and ambipolar diffusion times) are similar in both environments. Additionally, it is intriguing that the sound speed for a $T = 25$ K cloud is $a = 0.32$ km s$^{-1}$, very near the effective sound speed associated with typical star forming regions, as a star’s initial mass may depend sensitively on the temperature of the gas in which it is born (e.g., Adams & Fatuzzo 1996).

### 3. CONCLUSION

The fact that the physical conditions at the GC are quite different from those elsewhere in the Galaxy has often been cited as the reason why one might expect star formation to proceed differently there than out in the disk. But although the GC does contain a remarkable population of massive stars, the IMF in the Arches cluster appears to be consistent with the universal IMF observed throughout the rest of the galaxy.

Motivated by the ongoing debate about the nature of star formation, we have considered here how the extreme environmental conditions observed at the GC may affect the star formation process within the context of the standard paradigm. Specifically, we have explored the loss of magnetic support in dense ($n \sim 2-10 \times 10^7$ cm$^{-3}$), highly ionized ($\zeta \sim 1-4 \times 10^{-16}$ s$^{-1}$), and cool ($T \approx 25$ K) molecular cores located within the GC region. We find that while the higher ionization rates at the GC imply a strong coupling between the magnetic field and the neutral medium for most of the GC molecular gas, the resulting effect on ambipolar diffusion is offset by the higher densities associated with this region. As such, the ambipolar diffusion timescales in the dense regions of the GC are comparable to those associated with dense star-forming cores in typical GMCs. However, magnetic turbulence in the dense regions of the GC is suppressed for length scales below $\lambda_e \sim 10^{17}$ cm, owing to the strong damping of Alfvén and fast MHD waves. The corresponding loss of pressure is expected to lead to the formation of condensations with masses $\sim$0.1–30 $M_\odot$. While this mechanism parallels the process which sets the length scale at which ambipolar diffusion becomes significant and fragmentation or core formation is initiated in typical GMC environments (Mouschovias 1987, 1991; Mouschovias & Psaltis 1995), the resulting condensations at the GC may significantly exceed their Jeans limit ($\sim$0.3–0.9 $M_\odot$). Fragmentation of such condensations is unlikely to yield a core mass function similar to those observed from nearby star-forming regions. As such, a star formation scenario in which the IMF mimics the condensation mass function would not be consistent with observations. It is interesting to note, then, that the sound speed for a 25 K molecular cloud is 0.32 km s$^{-1}$, nearly the same as the effective sound speed associated with nearby star-forming cores. This result may then be taken as evidence favoring a scenario in which stellar processes which depend primarily upon physical parameters such as the local sound speed set a star’s initial mass (e.g., Adams & Fatuzzo 1996; Ciolek & Basu 2006).

On a final note, we note that the ambipolar diffusion time in both the dense regions of the GC and star-forming cores in typical GMCs is $\sim$1 Myr. While the issue of a cloud’s lifetime remains open, recent work has established the ages of typical clouds to be $\sim$10 Myr (Goldsmith et al. 2007). This result is consistent with the idea that the effective sound crossing time yields a reasonable estimate for how long clouds can survive. For a typical GMC environment, one thus infers a cloud lifetime of $\tau_{\text{cloud}} \approx 40$ pc/(1 km s$^{-1}$) $\sim$ 40 Myr. In contrast, the GC molecular clouds’ lifetimes are inferred to be $\sim$1–3 Myr. If condensations are initially supported by slow MHD waves, their collapse would occur on an ambipolar diffusion timescale, rather than the free-fall timescale. The fact that $\tau_{\text{AD}} \sim \tau_{\text{cloud}}$ at the GC may then help explain the low star formation efficiency in the GC region (Gordon et al. 1993).

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