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Abstract. The abundant gas in the central molecular zone of our Galaxy is forming stars at at about the same pace, per unit mass of gas, as the disk of the Galaxy, despite the very different physical conditions in the central environment: a strong dipole magnetic field, strong tidal forces, and a large internal velocity dispersion within the abundant molecular clouds. There are at least two pronounced differences in the properties of the stars that form near the center, as compared with the disk, however. First, among the stars which form near the Galactic center, the abundance of those with higher masses is relatively large, compared to the initial mass function elsewhere. Second, an important fraction of the stars that form near the center has recently been born into massive stellar clusters. I discuss these findings and argue that the same considerations apply to most, if not all gas-rich spiral galaxies. In the mass budget of the Galactic center, star formation is apparently the dominant sink.

1 Introduction

In the potential well of a galactic nucleus, where the gas density, the energy density, and the interstellar pressure are all large relative to a galactic disk, the conditions for star formation are quite different than one finds elsewhere. Perhaps because interstellar gas in a galactic nucleus has almost nowhere else to go but into star formation, if not deeper into the well, the surface density builds up until it reaches a steady state with the star formation process. The process is presumably regulated by the rate at which gas can be brought into the central molecular zone (CMZ). The best understood example is the CMZ of our Galaxy, which shows a very pronounced gas concentration, with about 5 x 10^7 $M_\odot$ of molecular gas concentrated into a region of radius less than 200 pc. In this region, star formation is apparently quite active, although we see only the high-mass stars, and note that they have a propensity to form in rather spectacular clusters. In contrast, star formation is only weakly in evidence near the nucleus of M31, but in that case, it is because of the relative dearth of gas there. In this paper, we are not concerned with the mechanisms such as mergers and angular momentum loss processes which bring gas into a galactic nucleus, but rather with the question of how stars can form once the gas is present. One clear determinant of star formation seems to be the molecular cloud surface density. Other factors include the internal velocity dispersion and the magnetic field strength within clouds, the effects of tidal forces, and the large pressure of the interstellar medium. In this paper, I first discuss each of these effects and

then their overall implications for the mode of star formation and the initial mass function. Then, the formation of compact, massive star clusters is considered; it seems likely that they form in relatively sudden cataclysms. Finally, I examine the mass budget of the galactic center reservoir of gas, concluding that star formation is probably the predominant mass sink.

2 Factors Playing a Role in Star Formation near a Galactic Nucleus

2.1 The Surface Density of Clouds

The surface density of molecular gas, Σ_{H_2}, is a predictor of the star formation rate, SFR, not only because the presence of more gas implies more fuel for star formation, but also because, for a fixed scale height of the gas, a greater surface density of molecular clouds implies more frequent cloud collisions - a likely trigger for star formation. In addition, the effectiveness with which star formation and young, massive stars can stimulate further star formation in nearby gas via stellar winds, collimated protostellar outflows, supernovae and radiation pressure is presumably a strong function of how much gas is nearby, *i.e.*, of Σ_{H_2}.

Overall, the dependence of SFR upon Σ_{H_2} can be parameterized in terms of the Schmidt Law, $\Sigma_{SFR}\ \alpha\ \Sigma_{H_2}^{\beta}$, where Σ_{SFR} is the surface density of star formation, and β is found empirically to be $\sim$1.4 [18] for galactic nuclei. The SFR for the nuclear region of the Milky Way has been inferred from the combination of the total far-infrared and radio continuum luminosities [10,2]. The bolometric luminosity in the central $3^\circ \times 2^\circ$ is 10^9 $L_\odot$ and the 5 GHz radio flux (2500 Jy) implies a total of $\sim 10^{52}$ Lyman continuum photons. The implied SFR is 0.3 (0.1 – 0.6) $M_\odot$ yr^{-1}, or about 10% of the SFR of the entire galaxy. Thus, the Milky Way fits reasonably well onto the Schmidt Law for galactic nuclei, if one adopts a total mass and radius of the CMZ as 5×10^7 $M_\odot$ and 200 pc, respectively. In the plot of the Schmidt law given in [18] (Fig. 7), the value of Σ_{SFR} is about a factor of 3 above the mean for its range of Σ_{H_2}, but is still within the distribution of values exhibited by other galaxies. I caution that the SFR rate used in this analysis is quite uncertain, however, both for our Galactic center and for other galactic nuclei. In particular, the conversion of radio flux and luminosity into stellar mass has been made using a standard initial mass function (IMF), whereas the true IMF in galactic nuclei probably favors massive stars ([6] and below) and may have an elevated lower mass cutoff [27]. Consequently, since massive stars dominate both the luminosity and the Lyman continuum flux, it should not be surprising if the actual SFR is lower than that presented here. If the SFR in the CMZ is only about 0.1 $M_\odot$ yr^{-1}, then it agrees better with other galaxies in the Schmidt Law plot.

2.2 Large Internal Velocity Dispersion of Clouds

The velocity dispersion measured for molecular clouds in the CMZ, even at the highest spatial resolutions obtainable, has been found to be uniformly much

larger than that of clouds in the Galactic disk. Typical measured linewidths (full width at half maximum) are 25 km s^{-1} [10]. Comparable or even larger linewidths are measured toward nearby galactic nuclei, but those linewidths are usually broadened by unresolved galactic dynamics. Only in almost face-on systems like IC342 [26] can we infer that a large velocity dispersion within clouds near the nucleus is probably a general phenomenon. While molecular clouds in the CMZ are unusually warm, 50 – 80 K ([31,16] in our Galaxy, and, *e.g.*, [12,15] in others), the observed linewidths are clearly not thermal.

A variety of sources for the internal cloud velocity dispersion can be imagined, including stellar winds, cloud collisions, tidally-induced shear flows, Alvén waves, and magnetosonic waves. The strong magnetic fields found in the Galactic center lend credence to these latter two possibilities, although direct measurements of the magnetic field strengths within clouds of the CMZ population have yet to be made.

The effect of the large velocity dispersion, Δv, can be gleaned from its effect on the Jeans mass, $M_J \ \alpha \ \Delta v^3/\rho^{1/2}$. For $\Delta v = 15$ km s^{-1} and molecular hydrogen density $10^4 n_4$ cm^{-3}, $M_J = 2 \times 10^5 \ M_\odot n_4^{-1/2}$. This rather large value corresponds better with the masses of the compact young clusters near the Galactic center than it does with individual stellar masses, but it may be indicative of a propensity for relatively massive stars, compared to star formation in the much more quiescent clouds of the Galactic disk. The velocity dispersion is relevant to the Jeans mass only if the scale of the velocity fluctuations is less than the Jeans length, 13 pc $n_4^{-1/2} \times (\Delta v/15 \ km \ s^{-1})$, a condition which is satisfied observationally.

An alternative way of describing the effect of the large velocity dispersion in CMZ clouds is to note that the pressure of the interstellar medium near the Galactic center is 2 or 3 orders of magnitude higher than that in the disk. Spergel & Blitz [41] argue that the turbulent pressure in clouds is likely to be in equilibrium with the thermal pressure of the X-ray-emitting coronal gas in which Galactic center clouds are bathed [46]. The high pressure may impede star formation if the Jeans mass is larger than the cloud clumps. In any case, the high pressure environment alters the boundary conditions for star formation, just as it does in cooling flows and elliptical galaxies [4,17].

2.3 The Magnetic Field

Current evidence indicates that the magnetic field strength within at least the inner ~100 pc is on the order of a milligauss, and that the large scale field geometry is dipolar. These conclusions are based on the presence of about a dozen nonthermal radio filaments (NTFs) which have been found there [28,29,23,22,33], several of which are shown in Figure 1. These NTFs, typically 50 – 100 pc long and only ~0.3 pc wide, are believed to be magnetic flux tubes which are part of a pervasive field, but which happen to be illuminated by the synchrotron emission from locally injected relativistic electrons [37]. The predominant orientation of the NTFs perpendicular to the Galactic plane, and in many cases

Fig. 1. Radiograph of 20cm emission intensity from the Galactic center, from [23]. The asterisks mark the locations of the Quintuplet (left) and Arches (right) clusters. The vertical extent of the region shown is 60 pc. The galactic plane is oriented in position angle -30°. The nonthermal radio filaments which presumably delineate the magnetic field are the thin structures oriented largely perpendicular to the Galactic plane. Several other sites of star formation are evident as HII regions to the north and east of the saturated SgrA complex, located at the bottom left of the figure.

passing through the plane, suggests the globally dipole geometry of the field. The curvature of the NTFs and the progression of orientation with galactocentric distance are consistent with a divergence of the field on a few-hundred-parsec scale. The milligauss field strength is estimated from the strikingly smooth curvature of the NTFs, in spite of the expected tumult of the interstellar medium in which they are embedded, and in spite of the large velocity dispersion and the presumably large relative motion of the clouds with which they are apparently interacting. The resistance of the NTFs to deformation implies a rigidity which yields a lower limit to the field strength.

The origin of the central dipole field may lie in a natural and inevitable process, and may be common to all spiral galaxies with a sufficiently large gas content. The following model, originally outlined by Sofue & Fujimoto [40], and further developed by Morris [28], has recently been considered in some detail by

Chandran et al. [1]: gas flows radially inward toward the nucleus from throughout the Galaxy as it loses angular momentum by a variety of processes, including torquing and shocking by the Galactic bar, spiral density wave shocks, galactic mergers, and mass accumulation from a low-angular-momentum halo. The vertical component of the protogalactic field is therefore concentrated at the center, even allowing for ambipolar diffusion, because the rate of outward radial diffusion of this component cannot compete with the inward flux of the matter to which it is largely frozen. The horizontal component is much more complex, because, while it can indeed diffuse outward through the thickness of the galactic gas layer in a Hubble time, it can be amplified by a variety of dynamo processes, including simple galactic shear resulting from differential rotation. Shear can also tap the vertical flux to produce horizontal flux, but overall, the vertical flux is conserved. Its fate is to be concentrated toward the center until some quasi-static equilibrium is established between the dynamical pressure of incoming gas and the reverse magnetic pressure gradient of the central vertical field. Inasmuch as this model is applicable to all spiral galaxies, the implications are profound for activity in galactic nuclei: AGN activity and star formation both occur in the presence of a strong magnetic field.

How does the milligauss field affect star formation in the Milky Way? First, it is instructive to examine the magnetic Jeans mass for magnetic flux density B: $M_J(B)\ \alpha\ B^3/n^2$. Again, ignoring the anisotropy of the Jeans length in this case, $M_J(B)$ is on the order of 10^5 $M_\odot$ for B $\sim$ 1 milligauss, reflecting an approximate equipartition of magnetic and kinetic energies within clouds of the CMZ. If the clouds' velocity structure is dominated by magnetohydrodynamic waves, then this result is equivalent to that arrived at in the above discussion of the velocity dispersion. The second conclusion that one must face is that the details of the star formation process itself (angular momentum transport, etc.) are strongly affected by the field. Finally, it should not be too surprising if the relatively massive stars which form are themselves highly magnetized.

2.4 Tidal Forces

The stability of clouds near the Galactic center against tidal shear requires n > $10^7\ cm^{-3}\ (1.6\ pc/r)^{1.8}$, for galactocentric radius r ([11] this applies to clouds which are more or less on circular orbits). For example, the parent cloud of the Arches cluster, which lies at $r\ \sim$ 30 pc, would need to have had a density exceeding $5 \times 10^4\ cm^{-3}$ in order to remain bound. This condition selects for star formation out of denser gas than might otherwise be required, and insofar as the magnetic field is flux frozen to slightly ionized molecular gas as it evolves to become denser, giving B α $n^{2/3}$, the magnetic Jeans mass is unaffected. Also, while tidal shear may prevent a cloud in the CMZ from being gravitationally bound, the unbound gas does not leave the region. Much of the gas in the CMZ appears to be present in the form of streams of orbiting gas (*e.g.*, [39]) which, while maintaining their integrity over a few dynamical times by being pressure-bound [41], remain gravitationally unbound until accumulation of ambient material and

collisions between these streams enhance their density past the point of gravitational stability.

Tidal forces can also be compressive for clouds moving inwards on predominantly radial orbits, because the clouds are moving into a converging gravitational field. In this case, the magnetic Jeans mass rises toward the center because the density and the magnetic flux density both rise as r^{-2}. Examples of approximately radially infalling gas streams can be seen in SgrA West, where the expected compression is perhaps demonstrated by the morphology of the leading tips of the infalling gas streams [30]. The dynamical time of the SgrA West features is probably too short ($\sim 10^4$ yr) to allow for star formation, but we note that star formation in radially infalling clouds located further out would give rise to stars on highly eccentric orbits. Some of the orbits of young stars in the central parsec [9] are consistent with star formation having occurred in radially infalling clouds.

2.5 Some Implications for Star Formation near a Galactic Nucleus

The ensemble of the effects described above implies a tendency for galactic nuclei to favor high mass star formation, relative to star formation further out in a galactic disk [27]. Thus, one might anticipate that the IMF is flatter in the CMZ of a galaxy than elsewhere. The existence of a lower mass cutoff to the IMF has also been considered as a possible consequence of the above effects (see discussion and references in [27]), although direct evidence of that is currently lacking. Observationally, the results for the IMF are currently mixed. For a power-law IMF, with $dN/dm \sim m^{-\alpha}$ (where $\alpha = 2.35$ is the Salpeter slope), one finds $\alpha = 1.5$ to 2.5 describing galactic nuclei. The massive, compact young clusters near the Galactic center have a relatively flat mass function, although they have already suffered a significant amount of dynamical evolution [19,20]. For further discussion of the IMF, I refer the reader to the review of Figer in this volume [6].

Although the observations are not definitively thorough, some prominent clouds in the CMZ of our Galaxy show little or no star formation. The "50 km s^{-1} cloud" is an interesting case; it harbors massive star formation along a dense ridge near its western extremity, as evidenced by the G-0.02-0.07 HII regions [3]. The compression of this ridge seems likely attributable to the expansion of the powerful SgrA East nonthermal shell source, presumably a supernova remnant (reference [24] and references therein). But the rest of this massive cloud has no known compact HII regions, IR-luminous embedded sources, H_2O masers or any other signs of star formation. By contrast, the less massive and somewhat less dense Orion Molecular Cloud has many apparent sites of star formation along its length. Thus, the "50 km s^{-1} cloud" is apparently impeded from forming stars in a piecemeal fashion, except where it has been subjected to a violent external shock. One might posit that this is the kind of powder keg that can form a starburst cluster if the shock is of sufficient strength, or if the cloud undergoes a global instability after growing to sufficient size. Another very massive molecular cloud in the CMZ, SgrB2, may now be undergoing just such a fate, as it is forming

a sizeable cluster of massive stars [25,7], possibly as a result of the collision of two large clouds [13].

3 Starburst Clusters in Our Galaxy and Elsewhere

One of the remarkable findings that has occured over the past decade concerning young stars in galactic nuclei is that massive, compact young clusters are abundant where star formation in occuring at a relatively high rate. This takes its most extreme form in starburst nuclei, where super-star clusters having masses ranging up to 10^6 $M_\odot$ are widely recognized to be commonplace (*e.g.,* [14,35,36,43]). Giant compact HII regions found in local dwarf galaxy starbursts are another indication of the formation of extremely massive, compact clusters [44,45,21].

In our Galaxy, we have the smaller, but still spectacular Arches and Quintuplet clusters [5], and the cluster of young stars occupying the central parsec (*e.g.,* [34]). These are the most massive young clusters in our Galaxy. The first two of these are doomed to tidal disintegration on a time scale less than 10^7 years [19,20], so one may conclude, with unimpressive statistical significance, that their rate of production is on the order of one every few million years, giving a massive cluster SFR of 0.01 $M_\odot$ yr^{-1}. This estimate assumes an initial cluster mass of $\sim 2 \times 10^4$ $M_\odot$ [20]. Comparison with the overall SFR of 0.3 $M_\odot$ yr^{-1} suggests that these massive clusters may be a minor contributor to the overall SFR of our Galactic center. However, in the nuclei of starburst galaxies, the formation of clusters may be the preferred mode of star formation (*e.g.,* [43]). An interesting hypothesis to consider is that, of the mass undergoing star formation near a galactic nucleus, the fraction which goes into massive, compact clusters is larger for more intense starbursts. The fact that starburst clusters are so much more populous, massive and compact than other known incidences of star formation suggests that the circumstances of their formation were peculiar in some fundamental way, such as catastrophic formation by extremely strong shocks or direct collision of two dense molecular clouds. These factors are presumably enhanced in high-surface-density starburst galaxies.

The compactness and high mass of the Arches cluster or any other starburst cluster raises the issue of the time scale over which the cluster must have formed. The violence implied by the formation of hundreds of O stars within a few tenths of a parsec, including protostellar jets and winds and ionized gas flows at ionization fronts, is likely to quickly shut off star formation once the process begins. Indeed, these clusters may begin formation on the scale of a Jeans mass, and then fragment hierarchically to stellar masses on a free-fall time scale. If so, then there is little room for the persistence of straggler gas clumps; the released gravitational energy rushing outward from the star formation cataclysm will commit any gas clump to immediate collapse or to a quick oblivion via ionization and Kelvin-Helmholtz instabilities. Massive starburst clusters must be quite close to coevality, so their use as probes of the IMF should be little affected by a spread in stellar ages.

4 Star Formation and The Galactic Center Mass Budget

It is instructive to review the role of star formation in the overall mass budget of interstellar gas in a galactic nucleus. Indeed, it is the dominant sink for the gas in a galactic nucleus.

Mass accretes from the disk of our Galaxy at a rate which can be estimated by noting that the molecular ring which defines the outer edge of the CMZ and contains a total of $\sim 8 \times 10^6$ $M_\odot$ [39] lies at about the location of the inner Lindblad resonance (ILR), coinciding with the innermost X1 orbit [8]. The fact that gas on this cusped orbit cannot reside there for more than about one orbital period leads to an estimate of the mass inflow rate: $\dot{M}_{ILR} = 0.4$ (0.1 - 1) $M_\odot$ yr^{-1}. No direct (*i.e.,* kinematic) evidence for this mass inflow is yet available, but it is inevitable in the face of the processes that cause angular momentum loss by the gas [32].

With such an inflow rate, we can estimate the residence time for gas in the CMZ: $\tau \sim M_{CMZ}/\dot{M}_{ILR} \sim 5 \times 10^8$ yr, which is comparable to the time scale for angular momentum loss by clouds within the CMZ as a result of dynamical friction [42] and magnetic viscosity [28].

While these estimates are crude, the apparently close correspondence between the star formation rate and the rate of gas inflow to the CMZ is intriguing, and may imply a steady state wherein star formation is sustained at its present rate over long periods of time [38]. Other contributors to the mass budget include (see ref. [32]): (1) the rate at which bulge stars shed mass which falls directly into the CMZ: a few times 0.01 $M_\odot$ yr^{-1}, (2) accretion onto and through the circumnuclear disk (0.03 – 0.05 $M_\odot$ yr^{-1}, (3) accretion onto the central black hole ($10^{-5} - 10^{-8}$ $M_\odot$ yr^{-1}), and (4) mass outflow in a thermally-driven coronal wind (0.03 – 0.1 $M_\odot$ yr^{-1}) [46]. The latter contribution is the most significant of these; if the SFR in the CMZ of our Galaxy should be lowered from the above estimates because of the altered IMF, then the mass loss rate in the coronal wind may be comparable to the rate of star formation. Forthcoming evidence from the Chandra and XMM Observatories should help clarify this point.

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