Astro2020 Science White Paper

What is the lifecycle of gas and stars in galaxy centers?

Thematic Areas:
☐ Star and Planet Formation
☐ Galaxy Evolution

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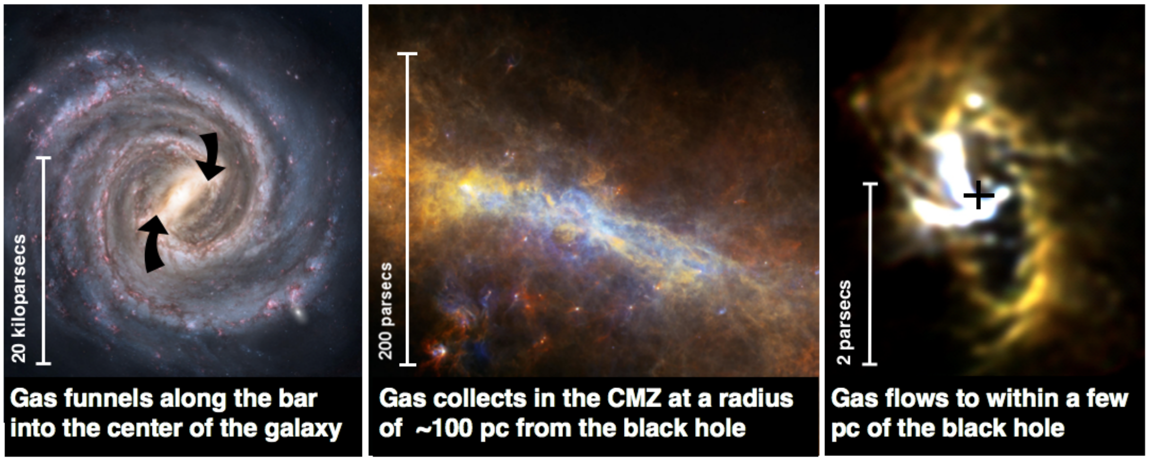
ABSTRACT

The closest galaxy center, our own Central Molecular Zone (CMZ; the central 500 pc of the Milky Way), is a powerful laboratory for studying the secular processes that shape galaxies across cosmic time, from large-scale gas flows and star formation to stellar feedback and interaction with a central supermassive black hole. Research over the last decade has revealed that the process of converting gas into stars in galaxy centers differs from that in galaxy disks. The CMZ is the only galaxy center in which we can identify and weigh individual forming stars, so it is the key location to establish the physical laws governing star formation and feedback under the conditions that dominate star formation across cosmic history. Large-scale surveys of molecular and atomic gas within the inner kiloparsec of the Milky Way ($\sim 10^\circ$) will require efficient mapping capabilities on single-dish radio telescopes. Characterizing the detailed star formation process will require large-scale, high-resolution surveys of the protostellar populations and small-scale gas structure with dedicated surveys on the Atacama Large Millimeter/submillimeter Array, and eventually with the James Webb Space Telescope, the Next Generation Very Large Array, and the Origins Space Telescope.



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Our own Central Molecular Zone (CMZ; the inner 500 pc of our Galaxy) is the closest galaxy nucleus, and it is actively forming stars (Morris & Serabyn 1996). It is the only location suitable for studying star formation in hot, turbulent, high-pressure (Ao et al. 2013; Ginsburg et al. 2016; Krieger et al. 2017) molecular gas analogous to the environments of high-redshift galaxies (Kruijssen & Longmore 2013), in which most stars formed. The centers of galaxies have more scattered star formation efficiencies than their disks (Leroy et al. 2013; Usero et al. 2015; Bigiel et al. 2016; Gallagher et al. 2018), suggesting that galaxy centers undergo episodic cycles of bursty star formation and quiescence that may influence the growth of central black holes (e.g., Kruijssen et al. 2014; Krumholz et al. 2017; Torrey et al. 2017; Seo et al. 2019). We highlight two overarching questions that we can answer over the next decade: how is our Galactic center fed, and how does it digest gas into stars?

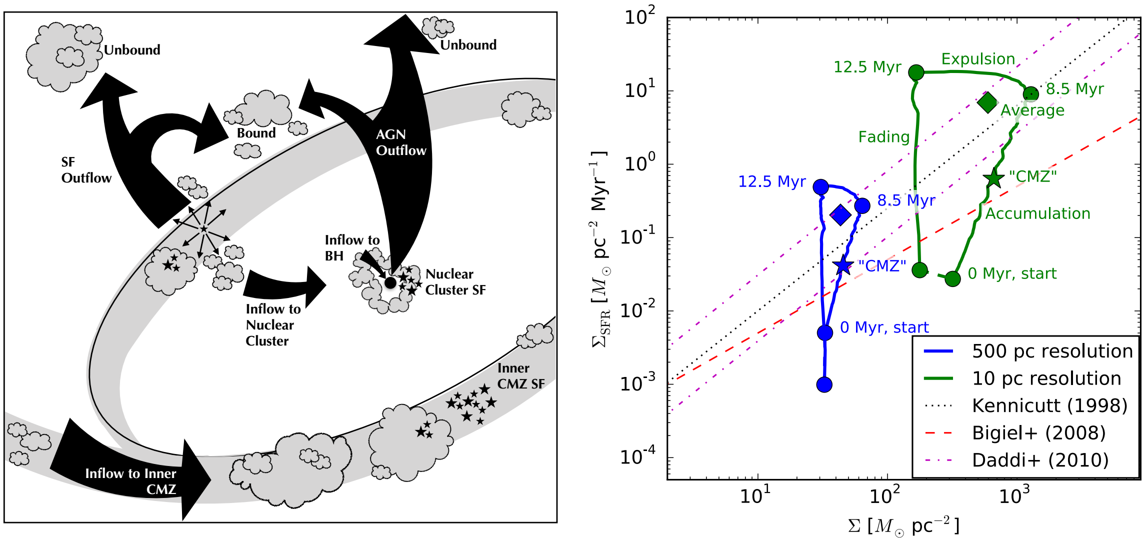

Figure 1. (left) A cartoon of the gas flows in and around the CMZ. Inflow from the Galactic bar feeds the CMZ, which contributes some material to star formation and some to the central black hole. Both the black hole and star formation drive feedback. (right) A summary figure from the Krumholz & Kruijssen (2015) dynamical model of CMZ gas cycles. The green and blue curves show the history of gas going through accumulation, star formation driven expulsion, and fading as the stars go out. They show these curves in observational parameter space of star formation rate surface density as a function of the gas surface density as would be seen at 10 and 500 pc resolution, respectively. The dashed curves show the fitted Kennicutt-Schmidt relations from Kennicutt (1998), Bigiel et al. (2008), and Daddi et al. (2010).

1. HOW IS GAS DEPOSITED INTO THE GALACTIC CENTER FROM THE GALACTIC DISK?

Fresh material arrives to the Galactic center from the disk via the Galactic bar. The star formation efficiency in the bar is lower than in much of the disk (e.g., Muraoka et al. 2019; Seo et al. 2019), which means fresh gas can be transported inward efficiently. A growing suite of simulations and analytic models (Krumholz &

Kruijssen 2015; Sormani et al. 2015; Torrey et al. 2017; Ridley et al. 2017; Krumholz et al. 2017; Sormani et al. 2018b; Jeffreson et al. 2018) demonstrate that galaxy centers vary between brief bursts of star formation followed by periods of quiescence given a variety of models of CMZ feeding. Secular dynamics set a barrier preventing the gas from moving inward, causing it to build up at $R_{gal} \sim 100$ pc, forming the CMZ (Krumholz & Kruijssen 2015). Gas transport further inward, to the nuclear cluster and the central black hole, is presently small (of the estimated $3{\times}10^7$ solar masses of molecular gas in the central 500 pc, only $1{\times}10^4$ solar masses is contained within the central $\lesssim 5$ pc) and may be driven primarily by stellar feedback (e.g., Davies et al. 2007; Kruijssen 2017; Sormani et al. 2018a). The infall through the final few parsecs is mediated by the circumnuclear disk (CND; e.g., Takekawa et al. 2017; Hsieh et al. 2017), which contains molecular and ionized gas at temperatures and densities seen nowhere else in the Galaxy (Mills et al. 2013, 2017).

Key questions about each step of the above inflow process that can be solved in the next decade include:

1. *Why is the star formation efficiency low in gas along the bar?* Very little star formation is currently known in the range 0.1 kpc $< R_{gal} < 3$ kpc, yet there is abundant molecular gas emission (e.g., Dame et al. 2001). Apparently, this gas is delivered to the CMZ with little loss to star formation. Why is it inefficient at forming stars until it reaches the Galactic center? Where is the material coming from, and how is it deposited on to the CMZ?

2. *How is gas transported from the CMZ to the central few parsecs?* After gas is delivered into the CMZ, models suggest that it stops flowing inwards, and instead builds up along orbital pathways until it reaches a critical threshold and begins forming stars (Kruijssen et al. 2014; Krumholz et al. 2017; Sormani et al. 2018a; Jeffreson et al. 2018). Shortly afterward, the feedback from high mass stars may dominate over the gas inflow, resulting in a net loss of gas from the CMZ. This feedback drives gas both inward, toward the central black hole, and vertically outward, producing an outflow. How much of this gas is turned into stars, how much is driven out of the Galactic center by feedback, and how much is driven towards the central black hole? What processes govern each of these steps?

Our Galactic center is presently at a low state in both star formation and accretion onto Sgr A*. The Fermi bubbles suggest there was much higher activity in the recent past (Su et al. 2010), but the present-day outflow activity is low and consistent with driving mostly by star formation (Law et al. 2009; Law 2010) with some contribution from Sgr A*'s jet (Muno et al. 2008; Li et al. 2013; Zhu et al. 2018). Tracking the present-day gas flow from outside the CMZ to the central black hole is critical to understand where gas resides during the low-state in galaxies.

The key advance needed to measure the lifecycle of gas in the Galactic center and the feeding of the central black hole is an accurate three-dimensional model of the central $R_{gal} \lesssim 100$ pc. Significant improvements in our understanding of the CMZ's geometry have been made in the last decade, refining the structural model of the molecular gas from a simple ring to a more realistic and physically self-consistent set of streams (Molinari et al. 2011; Kruijssen et al. 2015; Ridley et al. 2017; Sormani et al. 2018b; Kruijssen et al. 2019). Geometric tests are the most important tool to distinguish between the competing models.

Detailed observational work testing these models has so far progressed only piecemeal, with case studies assessing the line-of-sight locations of individual clouds and streams (e.g., Henshaw et al. 2016; Butterfield et al. 2018). Systematic studies comparing absorption and emission lines at multiple wavelengths, e.g., using centimeter-wave absorption lines of molecular species like H_2CO, OH, and C_3H_2, and emission from radio recombination lines, CO, and other bright molecular transitions in the millimeter range, have the potential to provide definitive locations of clouds and HII regions and test the theoretical geometric models. Assembling a geometric model will require systematic CMZ-wide (i.e., $\gtrsim 2^\circ \times 1^\circ$) maps capable of resolving individual clouds and HII regions ($\lesssim 30''$, ~ 1 pc).

Much of the molecular gas along the bar has only been observed at extremely coarse resolution (Dame et al. 2001). While these observations are useful for bulk mass inflow measurements (e.g., Sormani & Barnes 2019), they are inadequate for measurements of turbulence and star formation. Single-dish molecular line surveys at moderate ($\sim 30''$) resolution covering the inner $\sim 20^\circ$ of the Galaxy are needed to spatially resolve and measure the turbulent density and velocity distributions of these clouds. These measurements also require continued development of the statistical tools to link observed gas kinematics and density distributions with the underlying physics (Koch et al. 2017; Burkhart 2018). Observing the gas around the CMZ is essential for determining how the accretion process, i.e., the interface between bar and CMZ orbits, affects the observed geometry and controls the inflow process.

Some of the above observational goals can be achieved with existing facilities and instruments. However, they require substantial time allocations with efficient instrumentation (e.g., wide-bandwidth and/or multi-pixel receivers) and therefore require long-term continued access to single-dish radio telescopes.

Multiwavelength observations add important independent information to the above geometric constraints. The iron K-α lines in the X-ray trace light echoes from individual high-energy events in the Galactic center, and monitoring and timing these events can provide direct distance constraints on clouds (e.g., Clavel et al. 2014; Churazov et al. 2017a,b; Terrier et al. 2018). Long-term continued access to X-ray imaging and spectroscopy is needed to continue these light echo experiments, which grow in power and value over time. Furthermore, future imaging surveys with the James Webb

Space Telescope (JWST) will provide detailed, high-resolution extinction maps. Use of JWST in the Galactic center relies on support for high-dynamic-range imaging, wide-area mapping modes. Localization of the extincted stars to the Galactic center will enable molecular cloud mapping analogous to those made of the local kiloparsec with, e.g., Pan-STARRS (Green et al. 2015). Wide-area dust emission and spectral line mapping with the Origins Space Telescope (OST) will probe the structure of, and turbulence in, CMZ clouds. Polarization mapping in the sub-mm with OST will be key to understanding the role of magnetic fields in star formation and gas flows in this region. By studying the closest example in exquisite detail, we hope to understand the processes that control the gas flows and star formation in galaxy centers and the feeding of central supermassive black holes.

Multi-wavelength observations of the CMZ require space telescope observing modes that can cover wide areas with high dynamic range.

2. HOW DOES STAR FORMATION CHANGE IN CMZ-LIKE ENVIRONMENTS?

The gas conditions in the Galactic center are substantially different from the rest of the Galaxy. Most of the gas mass is in a molecular state (Kennicutt & Evans 2012; Mills & Battersby 2017) and is warmer and denser than local molecular clouds, conditions that closely reflect those seen at the peak of the cosmic star formation history. The CMZ therefore best represents the dominant conditions for star formation in the Universe (Kruijssen & Longmore 2013). Star formation is different under these conditions. There is continued discussion that the IMF in the Galactic center massive clusters, the Arches and the Quintuplet, may be shallower than the canonical IMF (Hosek et al. 2019). The molecular gas in the CMZ forms stars at a much lower rate than comparable-density gas in the Galactic disk (Longmore et al. 2013), showing that star formation does not occur at a uniform density threshold (Kruijssen et al. 2014; Rathborne et al. 2014; Barnes et al. 2017; Walker et al. 2018; Ginsburg et al. 2018). Determining what drives the difference between Galactic disk and CMZ star formation will provide physical insight needed to understand cosmic star formation.

The key open questions about star formation in Galactic centers are:

1. What changes in the star formation process under conditions of higher temperature and density (and therefore pressure), cosmic and X-ray backgrounds, and stronger magnetic fields? Specifically, how do the star formation rate and the initial mass function change under these conditions?
2. How does episodic star formation progress? Is star formation in galaxy centers tied to specific spatial or temporal triggers, and do these triggers represent a distinct mode from galaxy disk star formation?

The key advance needed to address these questions is a complete census of the ongoing star formation activity in the CMZ, i.e., identification and measurement of all embedded protostars.

High-resolution imaging in the millimeter and submillimeter regime across the entire CMZ is needed to perform a census of the ongoing star formation. The CMZ constitutes the most confused and extincted line of sight in the sky, so the mid-infrared Spitzer survey has been deeply ineffective at measuring star formation in this region (Koepferl et al. 2015). Individual programs have begun to tally the protostars (Ginsburg et al. 2018; Lu et al. 2019; Walker et al. in prep.; Barnes et al. in prep.) and the SMA has completed a systematic survey (Battersby et al. 2017). However, a systematic deep and high-resolution survey, such as the proposed ALMA CMZ Exploration Survey (ACES, PI Longmore) is needed to directly measure the star formation rate via the counting of protostellar cores. Such a survey will also provide both the gas density and kinematic measurements needed to characterize the turbulence and link the gas and stars.

For the coming decade, ALMA and JWST will be the key instruments for providing the prestellar and stellar census, respectively. However, because ALMA is limited to the millimeter regime, it will have limited accuracy when determining embedded stellar properties due to the high dust optical depth in disks; the ngVLA will be required to directly measure the properties of the most deeply hidden protostars. Very high-resolution ($\sim$ 100 AU) long-baseline observations with the ngVLA in the 70-120 GHz range will measure the kinematics of protostellar disks, providing a direct probe of protostellar masses. JWST will provide both a census of the young, recently formed stellar population and detailed dust extinction maps. OST will be needed to obtain luminosity measurements of the most embedded stars and high-resolution maps of dust density. The key needs this science program imposes on the space telescopes are mapping speed and dynamic range; the Galactic center is full of faint features adjacent to some of the brightest on the sky, and we need instruments and observing modes capable of detecting both.

Measuring star formation in the CMZ requires high-resolution observations over wide areas. ALMA, the JVLA and ngVLA, JWST, and OST provide these capabilities. Wide-area, high-resolution, and high-dynamic range capabilities should be prioritized.

Large-scale mapping of CMZ gas will enable comparison of our Galactic center to nearby galaxies (e.g., Leroy et al. 2018). Recent and ongoing ALMA surveys are providing tens of parsec-scale observations of nearby galaxies covering large areas with a few lines (PHANGS-ALMA, Leroy et al. in prep) or CMZ-scale areas across the entire millimeter spectrum (ALCHEMI). Analogous data sets covering our own CMZ are needed to generalize the Galactic work to extragalactic systems. Surveys of the molecular chemistry across the CMZ are needed to provide indirect means of understanding the physical scales that will remain unresolved in external galaxies. Studies of the CMZ will connect Galactic to extragalactic studies of star formation, provided that wide-field mapping capabilities are available.

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