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Article

Constraints on the Distribution of Gas and Young Stars in the Galactic Centre in the Context of Interpreting Gamma Ray Emission Features

Steven N. Longmore ^{1,*}  and J. M. Diederik Kruijssen ² 

¹ Astrophysics Research Institute, Liverpool John Moores University, 146 Brownlow Hill, Liverpool L3 5RF, UK

² Astronomisches Rechen-Institut, Zentrum für Astronomie der Universität Heidelberg, Mönchhofstraße 12-14, 69120 Heidelberg, Germany; kruijssen@uni-heidelberg.de

* Correspondence: s.n.longmore@ljmu.ac.uk

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Abstract: Gamma ray observations have found evidence of an extremely energetic outflow emanating from the Galactic Centre, and an ‘excess’ of emission at GeV energies towards the Galactic Centre over that expected from current models. Determining whether the outflow is AGN- or star formation-driven, and whether the ‘excess’ is astrophysical in origin or requires new physics (e.g., self-annihilation of dark matter), requires the accurate modelling of the expected energy injection from astrophysical sources and the subsequent interaction with the surrounding environment. We briefly summarise current constraints on the distribution of gas and young stars in the inner few hundred parsecs of the Galaxy that can be included in future 2D and 3D modelling of the astrophysical gamma ray emission. The key points to highlight with respect to predominantly axisymmetric models currently in use are: (i) the distribution of dense gas, young stars and interstellar radiation field is highly asymmetric around the Galactic Centre; (ii) star formation is almost exclusively constrained to a Galactocentric radius of ~ 100 pc; and (iii) the star formation rate in this region has been constant at $\lesssim 0.1 M_{\odot} \text{yr}^{-1}$ to within a factor of 2 over the last ~ 5 Myr.

Keywords: galactic centre; star formation; interstellar medium; Fermi bubble; galactic centre gamma ray excess

1. Introduction

Hosting our nearest supermassive black hole, sites of recent extreme star formation activity, and potentially large populations of compact accreting objects, the centre of our Galaxy is an ideal laboratory for studying high-energy physics [1]. Observations of the Galactic Centre from X-ray and gamma ray facilities (e.g., Fermi, HESS, Chandra, NuSTAR) are providing new insights into the energetic processes that shape the environment, probing the origin of cosmic rays, and even possibly the nature of dark matter through self-annihilation signals [2–8].

Given the implications for our understanding of mass flows and energy cycles in galactic nuclei and potentially even fundamental physics, major efforts are underway to determine the origin of these high-energy photons. Determining the astrophysical contribution to the high-energy photon distribution from different sources (e.g., star formation, supernovae, AGN episodes) relies on modelling the energy/momentum injection from relevant astrophysical sources and the subsequent interaction with the surrounding environment [9,10]. As well as accurate injection models, this requires knowing the relative locations of different injection sources and the variations in physical conditions (interstellar radiation field, gas density, gas temperature, magnetic field strength and morphology, etc.) across the Galactic Centre.

While the location of some injection sources are well constrained (e.g., the super-massive black hole, Sgr A*, and stars in the nuclear cluster), the distribution of other injection sources (e.g., young high-mass stars, supernovae) and the distribution of dense gas (the main reservoir of baryonic matter not trapped inside stars) are more uncertain. In this paper, we provide a brief overview of recent developments in our understanding of the relative distribution of dense gas and young stars. This is intended as an introduction to the current state of knowledge and to provide a feel for the inherent uncertainties rather than as an exhaustive review. Our primary goal is to focus on the implications of the distribution of dense gas and young stars for modelling the origin of high-energy photons in the Galactic Centre.

2. 2D Distribution of Dense (Molecular) Gas and Young Stars

As the solar system resides in the disc of the Galaxy, the first challenge in understanding the distribution of gas and young stars in the vicinity of the Galactic Centre is removing the contribution from foreground and background gas/stars. Figure 1 shows the distribution of dense gas (red) and young stars (blue) observed towards the inner few degrees in longitude of the Galaxy.

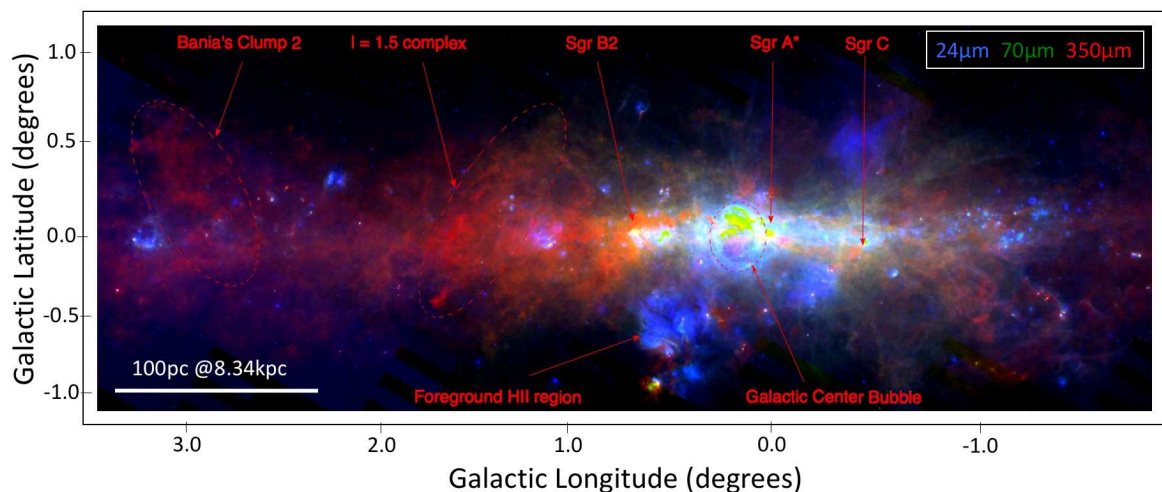


Figure 1. Three-colour image of the inner few degrees of the Milky Way around the Galactic Centre at sub-mm to mid-IR wavelengths (following [11,12]). Red and green show 350 μm and 70 μm emission (*Herschel* Hi-GAL [13]) and blue shows 24 μm emission (*Spitzer* MIPS GAL [14]). Sources of interest throughout the region are labelled. The scale-bar shows a projected length of ~ 100 pc at a distance of 8.34 kpc [15]. As the largest concentration of dense gas in the Galaxy by far and the site of some of the most extreme star formations in the Galaxy, the inner few hundred pc of the Galactic Centre is very bright in (sub)-mm continuum emission from dust associated with the gas (red), and mid-IR emission from dust heated by recently formed high-mass stars (blue).

Thankfully, it is straightforward to tell that almost all of the emission from gas in the inner few degrees longitude lies within a few hundred pc of the Galactic Centre. This is because the properties of molecular gas in the Galactic Centre are very different from the gas in the disc [1,16,17]. Spectral line observations of molecular rotational transitions show that the gas velocity dispersion is many times larger at fixed spatial scale [18–23]. The molecular gas in the Galactic Centre is also on average a factor ~ 100 times more dense and a factor 3–4 times warmer than gas in the disc [22,24,25]—conditions which excite more energetic rotational transitions that can be used to isolate gas at the Galactic Centre.

Similarly, it is possible to determine (e.g., from the measured extinction) that the vast majority of emission from young stars in the inner few degrees longitude must be coming from within a few hundred pc of the Galactic Centre. This region contains some of the most extreme recent star formations in the Galaxy. Sgr B2 is the most luminous star forming region in the Milky Way and often referred

to as the closest example of a “mini-starburst” [26–30]. At a projected distance, ~ 40 pc closer to the Galactic Centre than Sgr B2 (approximately at the location of the Galactic Centre Bubble annotation in Figure 1) lie the Arches and Quintuplet clusters, two of the most massive and dense young clusters in the Galaxy [31–33]. The nuclear cluster surrounding Sgr A* contains a population of very young and high mass stars (see [34] for a review). Finally, the very bright $24\ \mu\text{m}$ (blue) point sources at negative Galactic longitudes in Figure 1 are a population of massive young stellar objects (YSOs) and evolved high mass stars [35–37].

One of the most striking features of the 2D projected distribution of the dense gas and young stars is their strong asymmetry: 2/3 of the dense gas is at positive longitudes and 2/3 of the young stars are at negative longitudes [1]. Numerical simulations suggest asymmetries in the dense gas may arise from unsteady inflow of gas in the barred potential (e.g., [38–41]).

3. 3D Distribution of Dense (Molecular) Gas and Young Stars

3.1. 3D Distribution of Dense Gas

The main challenge in transforming the 2D distribution of gas and young stars into a 3D distribution is ascertaining the distance to different emission regions. There are many different methods for attempting to determine distances, each of which have their strengths and weaknesses. These methods can be separated into those that attempt to derive an absolute distance to an object, and those that try to infer the relative distances between objects.

Arguably the most robust absolute distance measurements come from cm-wavelength maser and continuum parallaxes. With multi-epoch VLBI observations, it is possible to fix the distance to bright objects (e.g., Sgr A* and masers in Sgr B2) with an uncertainty of a few percent [15]. With a model of the Galactic stellar population and the dust distribution along the line of sight to the Galactic Centre, it is also possible to derive an absolute distance to objects from near-IR extinction measurements. With an initial 3D framework tied down by these absolute distance measurements, it is possible to infer the relative position of different objects using other methods.

Combined with a model of the background stellar distribution (which dominates the gravitational potential), the change in the observed line-of-sight velocity of gas as a function of position provides an important handle on the location of the gas. From this, it has been inferred that the gas at positive longitudes (left) of Sgr B2 in Figure 1 is most likely at distances of a few hundred pc in the foreground, while the gas at negative longitudes (right) of Sgr C in Figure 1 is likely a few hundred pc in the background [42–44]. Unfortunately, current uncertainties in the distance mean we cannot localise the 3D position of any of this gas to better than a few hundred pc.

Fortunately, we have better constraints on the relative positions of gas and young stars in the inner 1 degree longitude (between Sgr B2 and Sgr C in Figure 1). Spectral line observations of molecular rotational transitions show that the majority of gas lies in clouds which are connected along a coherent gas stream [21,45–47]. Whether or not these clouds appear in absorption against the bright infrared background makes it possible to determine if they lie in front or behind the Galactic Centre. When combining this information with a model of the background stellar distribution (recall that it dominates the gravitational potential), one can derive the 3D distribution of the gas clouds from the change in the observed line-of-sight velocity of gas as a function of position [48,49]. Our current understanding is that most of the gas belongs to a stream of a few $10^7 M_{\odot}$ orbiting the centre at a radius of ~ 100 pc [49]. Interior to the 100 pc gas stream, the $10^4 M_{\odot}$ ‘circumnuclear disc’ and the ionised gas ‘mini-spiral’ both lie within a few pc of Sgr A*.

A particularly interesting constraint on the distance of certain gas clouds from Sgr A* comes from spatial variations in the intensity of X-ray emission across these clouds as a function of time [50]. The interpretation of these variations is that they are X-ray light echoes, where the source of X-rays is assumed to be from Sgr A* when it had a flare in X-ray brightness, presumably from a prior accretion

episode. With a model of the X-ray time variability of Sgr A*, one can infer the distance to clouds from the time lag since the outburst of their increasing X-ray brightness [51].

3.2. 3D Distribution of Young Stars

The nuclear star cluster, hosting a population of recently formed high-mass stars, is unambiguously situated in the inner pc of the galaxy surrounding Sgr A* [34]. The 3D location of the Arches and Quintuplet clusters is more difficult to ascertain. Measurement of their proper motion show they are moving with substantial velocity $>100 \text{ km s}^{-1}$ to positive longitudes (left in Figure 1) along the Galactic plane, consistent with them orbiting the Galactic Centre at a radius of $\sim 100\text{--}200 \text{ pc}$ [52–54]. Their orbital motions are consistent with them having formed in the 100 pc gas stream [49]. In the absence of distance and proper motion measurements, the 3D positions of the $24 \mu\text{m}$ point sources are relatively unconstrained. It has been postulated that these stars may be the remnants of an Arches/Quintuplet like cluster that has been destroyed by the tidal field (the tidal disruption timescale in this region of the Galaxy is 5–10 Myr: [55]). The fraction of young stars in bound clusters is difficult to ascertain due to incompleteness (observations are primarily sensitive to the youngest, most massive stars that only contain a small fraction of the young stellar mass budget), but appears close to 50%, consistent with theoretical predictions [56].

Almost all the current star formation activity and gas clouds just beginning to form are constrained to the 100 pc stream [30,57–70], as expected given the radial variation in environmental conditions within the inner few hundred pc of the Galaxy [71]. Observations that are sensitive to the star formation activity over different timescales show the rate of star formation has been constant to within a factor two of $0.1 \text{ M}_{\odot} \text{ yr}^{-1}$ for the last 5–10 Myr [72]. Although observations are unfortunately not sensitive to star formation rates on longer timescales, numerical simulations that resolve the large-scale ($\sim \text{kpc}$) gas flows show the inflow is stochastic [38–41] and the star formation may be episodic with long periods (20–40 Myr) of quiescence (star formation rate $\sim 0.1 \text{ M}_{\odot} \text{ yr}^{-1}$) followed by intense (few Myr) periods where star formation activity is enhanced by an order of magnitude or more [73,74]. This is a consequence of the background stellar potential, environmental conditions, gas properties and the natural physical scales and time scales of the star formation process in the inner few hundred pc of the Galaxy [75–77].

4. Implications for Future Modelling of the Gamma Ray Emission

The distribution of gas and young stars provides several important constraints on the relative locations of energy injection sources, the surrounding gas reservoir, and the variation in physical conditions throughout the region. Specifically:

1. 2/3 of the dense gas is at positive Galactic longitudes (left of Sgr A* in Figure 1).
2. 2/3 of the young stars are at negative Galactic longitudes (right of Sgr A* in Figure 1).
3. All of the current star formations are contained within a projected radius of 100 pc from the Galactic Centre.
4. The star formation rate in this region has been constant at $\sim 0.1 \text{ M}_{\odot} \text{ yr}^{-1}$ to within a factor of 2 over the last $\sim 5 \text{ Myr}$. Numerical modelling suggests that the star formation rate may have been at last an order of magnitude larger in the past, but this is currently unconstrained by observations.

The implications of this for modelling the origin of high-energy photons are that the interstellar radiation field, mass reservoir, etc., are highly asymmetric and often anti-correlated on both large and small scales. These large-scale offsets suggest the distribution of core-collapse supernovae may also be asymmetric around the Galactic Centre. In summary, modelling (i) energy injection from young stars and core-collapse supernovae, and (ii) the variations in physical conditions (interstellar radiation field, gas density, temperature, magnetic field) as purely radial or axisymmetric terms should be treated with caution.

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References

1. Morris, M.; Serabyn, E. The Galactic Center Environment. *Annu. Rev. Astron. Astrophys.* **1996**, *34*, 645–702. [[CrossRef](#)]
2. Aharonian, F.; Akhperjanian, A.G.; Bazer-Bachi, A.R.; Beilicke, M.; Benbow, W.; Berge, D.; Bernlöhr, K.; Boisson, C.; Bolz, O. Discovery of very-high-energy γ -Rays from the Galactic Centre ridge. *Nature* **2006**, *439*, 695–698. [[CrossRef](#)] [[PubMed](#)]
3. Goodenough, L.; Hooper, D. Possible Evidence for Dark Matter Annihilation in the Inner Milky Way from the Fermi Gamma Ray Space Telescope. *arXiv* **2009**, arXiv:hep-ph/0910.2998. [[CrossRef](#)]
4. Su, M.; Slatyer, T.R.; Finkbeiner, D.P. Giant Gamma-ray Bubbles from Fermi-LAT: Active Galactic Nucleus Activity or Bipolar Galactic Wind? *Astrophys. J.* **2010**, *724*, 1044–1082. [[CrossRef](#)]
5. Hooper, D.; Goodenough, L. Dark matter annihilation in the Galactic Center as seen by the Fermi Gamma Ray Space Telescope. *Phys. Lett. B* **2011**, *697*, 412–428. [[CrossRef](#)]
6. Hooper, D.; Linden, T. Origin of the gamma rays from the Galactic Center. *Phys. Rev. D* **2011**, *84*, 123005. [[CrossRef](#)]
7. Crocker, R.M.; Aharonian, F. Fermi Bubbles: Giant, Multibillion-Year-Old Reservoirs of Galactic Center Cosmic Rays. *Phys. Rev. Lett.* **2011**, *106*, 101102. [[CrossRef](#)] [[PubMed](#)]
8. Malyshev, D. Galactic center gamma-ray excess and the Fermi bubbles. *Nuovo Cimento C Geophys. Space Phys. C* **2018**, *40*, 159.
9. Crocker, R.M.; Jones, D.I.; Aharonian, F.; Law, C.J.; Melia, F.; Oka, T.; Ott, J. Wild at Heart: The particle astrophysics of the Galactic Centre. *Mon. Not. R. Astron. Soc.* **2011**, *413*, 763–788. [[CrossRef](#)]
10. Crocker, R.M. Non-thermal insights on mass and energy flows through the Galactic Centre and into the Fermi bubbles. *Mon. Not. R. Astron. Soc.* **2012**, *423*, 3512–3539. [[CrossRef](#)]
11. Bally, J.; Aguirre, J.; Battersby, C.; Bradley, E.T.; Cyganowski, C.; Dowell, D.; Drosback, M.; Dunham, M.K.; Evans, N.J., II; Ginsburg, A.; et al. The Bolocam Galactic Plane Survey: $\lambda = 1.1$ and 0.35 mm Dust Continuum Emission in the Galactic Center Region. *Astrophys. J.* **2010**, *721*, 137–163. [[CrossRef](#)]
12. Molinari, S.; Bally, J.; Glover, S.; Moore, T.; Noreiga-Crespo, A.; Plume, R.; Testi, L.; Vázquez-Semadeni, E.; Zavagno, A.; Bernard, J.P.; et al. The Milky Way as a Star Formation Engine. In *Protostars Planets VI*; University of Arizona Press: Tucson, Arizona, USA, 2014; pp. 125–148.
13. Molinari, S.; Swinyard, B.; Bally, J.; Barlow, M.; Bernard, J.P.; Martin, P.; Moore, T.; Noriega-Crespo, A.; Plume, R.; Testi, L. Clouds, filaments, and protostars: The Herschel Hi-GAL Milky Way. *Astron. Astrophys.* **2010**, *518*, L100. [[CrossRef](#)]
14. Carey, S.J.; Noriega-Crespo, A.; Mizuno, D.R.; Shenoy, S.; Paladini, R.; Kraemer, K.E.; Price, S.D.; Flagey, N.; Ryan, E.; Ingalls, J.G.; et al. MIPS GAL: A Survey of the Inner Galactic Plane at 24 and 70 μm . *Publ. Astron. Soc. Pac.* **2009**, *121*, 76. [[CrossRef](#)]
15. Reid, M.J.; Menten, K.M.; Brunthaler, A.; Zheng, X.W.; Dame, T.M.; Xu, Y.; Wu, Y.; Zhang, B.; Sanna, A.; Sato, M.; et al. Trigonometric Parallaxes of High Mass Star Forming Regions: The Structure and Kinematics of the Milky Way. *Astrophys. J.* **2014**, *783*, 130. [[CrossRef](#)]
16. Kruijssen, J.M.D.; Longmore, S.N. Comparing molecular gas across cosmic time-scales: The Milky Way as both a typical spiral galaxy and a high-redshift galaxy analogue. *Mon. Not. R. Astron. Soc.* **2013**, *435*, 2598–2603. [[CrossRef](#)]
17. Mills, E.A.C. The Milky Way’s Central Molecular Zone. *arXiv* **2017**, arXiv:1705.05332. [[CrossRef](#)]
18. Bally, J.; Stark, A.A.; Wilson, R.W.; Henkel, C. Galactic center molecular clouds. I—Spatial and spatial-velocity maps. *Astrophys. J. Suppl. Ser.* **1987**, *65*, 13–82. [[CrossRef](#)]
19. Bally, J.; Stark, A.A.; Wilson, R.W.; Henkel, C. Galactic center molecular clouds. II—Distribution and kinematics. *Astrophys. J.* **1988**, *324*, 223–247. [[CrossRef](#)]

20. Shetty, R.; Beaumont, C.N.; Burton, M.G.; Kelly, B.C.; Klessen, R.S. The linewidth-size relationship in the dense interstellar medium of the Central Molecular Zone. *Mon. Not. R. Astron. Soc.* **2012**, *425*, 720–729. [[CrossRef](#)]
21. Henshaw, J.D.; Longmore, S.N.; Kruijssen, J.M.D.; Davies, B.; Bally, J.; Barnes, A.; Battersby, C. Molecular gas kinematics within the central 250 pc of the Milky Way. *Mon. Not. R. Astron. Soc.* **2016**, *457*, 2675–2702. [[CrossRef](#)]
22. Ginsburg, A.; Henkel, C.; Ao, Y.; Riquelme, D.; Kauffmann, J.; Pillai, T.; Mills, E.A.C.; Requena-Torres, M.A.; Immer, K.; Testi, L. Dense gas in the Galactic central molecular zone is warm and heated by turbulence. *Astron. Astrophys.* **2016**, *586*, A50. [[CrossRef](#)]
23. Longmore, S.N.; Walsh, A.J.; Purcell, C.R.; Burke, D.J.; Henshaw, J.; Walker, D.; Urquhart, J.; Barnes, A.T.; Whiting, M.; Burton, M.G.; et al. H₂O Southern Galactic Plane Survey (HOPS): Paper III—Properties of dense molecular gas across the inner Milky Way. *Mon. Not. R. Astron. Soc.* **2017**, *470*, 1462–1490. [[CrossRef](#)]
24. Güsten, R.; Walmsley, C.M.; Pauls, T. Ammonia in the neighbourhood of the galactic center. *Astron. Astrophys.* **1981**, *103*, 197–206.
25. Mills, E.A.C.; Morris, M.R. Detection of Widespread Hot Ammonia in the Galactic Center. *Astrophys. J.* **2013**, *772*, 105. [[CrossRef](#)]
26. Scoville, N.Z.; Solomon, P.M.; Penzias, A.A. The molecular cloud Sagittarius B2. *Astrophys. J.* **1975**, *201*, 352–365. [[CrossRef](#)]
27. Gaume, R.A.; Claussen, M.J.; de Pree, C.G.; Goss, W.M.; Mehringer, D.M. The Sagittarius B2 Star-forming Region. I. Sensitive 1.3 Centimeter Continuum Observations. *Astrophys. J.* **1995**, *449*, 663. [[CrossRef](#)]
28. Schmiedeke, A.; Schilke, P.; Möller, T.; Sánchez-Monge, Á.; Bergin, E.; Comito, C.; Csengeri, T.; Lis, D.C.; Molinari, S.; Qin, S.L.; et al. The physical and chemical structure of Sagittarius B2. I. Three-dimensional thermal dust and free-free continuum modeling on 100 au to 45 pc scales. *Astron. Astrophys.* **2016**, *588*, A143. [[CrossRef](#)]
29. Sánchez-Monge, Á.; Schilke, P.; Schmiedeke, A.; Ginsburg, A.; Cesaroni, R.; Lis, D.C.; Qin, S.L.; Müller, H.S.P.; Bergin, E.; Comito, C.; et al. The physical and chemical structure of Sagittarius B2. II. Continuum millimeter emission of Sgr B2(M) and Sgr B2(N) with ALMA. *Astron. Astrophys.* **2017**, *604*, A6. [[CrossRef](#)]
30. Ginsburg, A.; Bally, J.; Barnes, A.; Bastian, N.; Battersby, C.; Beuther, H.; Brogan, C.; Contreras, Y.; Corby, J.; Darling, J.; et al. Distributed Star Formation throughout the Galactic Center Cloud Sgr B2. *Astrophys. J.* **2018**, *853*, 171. [[CrossRef](#)]
31. Figer, D.F.; Kim, S.S.; Morris, M.; Serabyn, E.; Rich, R.M.; McLean, I.S. Hubble Space Telescope/NICMOS Observations of Massive Stellar Clusters near the Galactic Center. *Astrophys. J.* **1999**, *525*, 750–758. [[CrossRef](#)]
32. Figer, D.F.; McLean, I.S.; Morris, M. Massive Stars in the Quintuplet Cluster. *Astrophys. J.* **1999**, *514*, 202–220. [[CrossRef](#)]
33. Figer, D.F.; Najarro, F.; Gilmore, D.; Morris, M.; Kim, S.S.; Serabyn, E.; McLean, I.S.; Gilbert, A.M.; Graham, J.R.; Larkin, J.E.; et al. Massive Stars in the Arches Cluster. *Astrophys. J.* **2002**, *581*, 258–275. [[CrossRef](#)]
34. Genzel, R.; Eisenhauer, F.; Gillessen, S. The Galactic Center massive black hole and nuclear star cluster. *Rev. Mod. Phys.* **2010**, *82*, 3121–3195. [[CrossRef](#)]
35. Yusef-Zadeh, F.; Hewitt, J.W.; Arendt, R.G.; Whitney, B.; Rieke, G.; Wardle, M.; Hinz, J.L.; Stolovy, S.; Lang, C.C.; Burton, M.G.; et al. Star Formation in the Central 400 pc of the Milky Way: Evidence for a Population of Massive Young Stellar Objects. *Astrophys. J.* **2009**, *702*, 178–225. [[CrossRef](#)]
36. Immer, K.; Schuller, F.; Omont, A.; Menten, K.M. Recent star formation in the inner Galactic bulge seen by ISOGAL. II. The central molecular zone. *Astron. Astrophys.* **2012**, *537*, A121. [[CrossRef](#)]
37. Koepferl, C.M.; Robitaille, T.P.; Morales, E.F.E.; Johnston, K.G. Main-sequence Stars Masquerading as Young Stellar Objects in the Central Molecular Zone. *Astrophys. J.* **2015**, *799*, 53. [[CrossRef](#)]
38. Renaud, F.; Bournaud, F.; Emsellem, E.; Agertz, O.; Athanassoula, E.; Combes, F.; Elmegreen, B.; Kraljic, K.; Motte, F.; Teysier, R. Environmental regulation of cloud and star formation in galactic bars. *Mon. Not. R. Astron. Soc.* **2015**, *454*, 3299–3310. [[CrossRef](#)]
39. Emsellem, E.; Renaud, F.; Bournaud, F.; Elmegreen, B.; Combes, F.; Gabor, J.M. The interplay between a galactic bar and a supermassive black hole: Nuclear fuelling in a subparsec resolution galaxy simulation. *Mon. Not. R. Astron. Soc.* **2015**, *446*, 2468–2482. [[CrossRef](#)]

40. Ridley, M.G.L.; Sormani, M.C.; Treß, R.G.; Magorrian, J.; Klessen, R.S. Nuclear spirals in the inner Milky Way. *Mon. Not. R. Astron. Soc.* **2017**, *469*, 2251–2262. [[CrossRef](#)]
41. Sormani, M.C.; Treß, R.G.; Ridley, M.; Glover, S.C.O.; Klessen, R.S.; Binney, J.; Magorrian, J.; Smith, R. A theoretical explanation for the Central Molecular Zone asymmetry. *Mon. Not. R. Astron. Soc.* **2018**, *475*, 2383–2402. [[CrossRef](#)]
42. Tsuboi, M.; Handa, T.; Ukita, N. Dense Molecular Clouds in the Galactic Center Region. I. Observations and Data. *Astrophys. J. Suppl. Ser.* **1999**, *120*, 1–39. [[CrossRef](#)]
43. Ferrière, K.; Gillard, W.; Jean, P. Spatial distribution of interstellar gas in the innermost 3 kpc of our galaxy. *Astron. Astrophys.* **2007**, *467*, 611–627. [[CrossRef](#)]
44. Rodriguez-Fernandez, N.J.; Combes, F. Gas flow models in the Milky Way embedded bars. *Astron. Astrophys.* **2008**, *489*, 115–133. [[CrossRef](#)]
45. Jones, P.A.; Burton, M.G.; Cunningham, M.R.; Requena-Torres, M.A.; Menten, K.M.; Schilke, P.; Belloche, A.; Leurini, S.; Martín-Pintado, J.; Ott, J.; et al. Spectral imaging of the Central Molecular Zone in multiple 3-mm molecular lines. *Mon. Not. R. Astron. Soc.* **2012**, *419*, 2961–2986. [[CrossRef](#)]
46. Henshaw, J.D.; Longmore, S.N.; Kruijssen, J.M.D. Seeding the Galactic Centre gas stream: gravitational instabilities set the initial conditions for the formation of protocluster clouds. *Mon. Not. R. Astron. Soc.* **2016**, *463*, L122–L126. [[CrossRef](#)]
47. Krieger, N.; Ott, J.; Beuther, H.; Walter, F.; Kruijssen, J.M.D.; Meier, D.S.; Mills, E.A.C.; Contreras, Y.; Edwards, P.; Ginsburg, A.; et al. The Survey of Water and Ammonia in the Galactic Center (SWAG): Molecular Cloud Evolution in the Central Molecular Zone. *Astrophys. J.* **2017**, *850*, 77. [[CrossRef](#)]
48. Molinari, S.; Bally, J.; Noriega-Crespo, A.; Compiègne, M.; Bernard, J.P.; Paradis, D.; Martin, P.; Testi, L. A 100 pc Elliptical and Twisted Ring of Cold and Dense Molecular Clouds Revealed by Herschel Around the Galactic Center. *Astrophys. J. Lett.* **2011**, *735*, L33. [[CrossRef](#)]
49. Kruijssen, J.M.D.; Dale, J.E.; Longmore, S.N. The dynamical evolution of molecular clouds near the Galactic Centre—I. Orbital structure and evolutionary timeline. *Mon. Not. R. Astron. Soc.* **2015**, *447*, 1059–1079. [[CrossRef](#)]
50. Clavel, M.; Terrier, R.; Goldwurm, A.; Morris, M.R.; Ponti, G.; Soldi, S.; Trap, G. Echoes of multiple outbursts of Sagittarius A* revealed by Chandra. *Astron. Astrophys.* **2013**, *558*, A32. [[CrossRef](#)]
51. Churazov, E.; Khabibullin, I.; Sunyaev, R.; Ponti, G. Not that long time ago in the nearest galaxy: 3D slice of molecular gas revealed by a 110 yr old flare of Sgr A*. *Mon. Not. R. Astron. Soc.* **2017**, *465*, 45–53. [[CrossRef](#)]
52. Stolte, A.; Ghez, A.M.; Morris, M.; Lu, J.R.; Brandner, W.; Matthews, K. The Proper Motion of the Arches Cluster with Keck Laser-Guide Star Adaptive Optics. *Astrophys. J.* **2008**, *675*, 1278–1292. [[CrossRef](#)]
53. Clarkson, W.I.; Ghez, A.M.; Morris, M.R.; Lu, J.R.; Stolte, A.; McCrady, N.; Do, T.; Yelda, S. Proper Motions of the Arches Cluster with Keck Laser Guide Star Adaptive Optics: The First Kinematic Mass Measurement of the Arches. *Astrophys. J.* **2012**, *751*, 132. [[CrossRef](#)]
54. Stolte, A.; Hußmann, B.; Morris, M.R.; Ghez, A.M.; Brandner, W.; Lu, J.R.; Clarkson, W.I.; Habibi, M.; Matthews, K. The Orbital Motion of the Quintuplet Cluster—A Common Origin for the Arches and Quintuplet Clusters? *Astrophys. J.* **2014**, *789*, 115. [[CrossRef](#)]
55. Portegies Zwart, S.F.; Makino, J.; McMillan, S.L.W.; Hut, P. The Lives and Deaths of Star Clusters near the Galactic Center. *Astrophys. J.* **2002**, *565*, 265–279. [[CrossRef](#)]
56. Kruijssen, J.M.D. On the fraction of star formation occurring in bound stellar clusters. *Mon. Not. R. Astron. Soc.* **2012**, *426*, 3008–3040. [[CrossRef](#)]
57. Longmore, S.N.; Rathborne, J.; Bastian, N.; Alves, J.; Ascenso, J.; Bally, J.; Testi, L.; Longmore, A.; Battersby, C.; Bressert, E.; et al. G0.253+0.016: A Molecular Cloud Progenitor of an Arches-like Cluster. *Astrophys. J.* **2012**, *746*, 117. [[CrossRef](#)]
58. Longmore, S.N.; Bally, J.; Testi, L.; Purcell, C.R.; Walsh, A.J.; Bressert, E.; Pestalozzi, M.; Molinari, S.; Ott, J.; Cortese, L.; et al. Variations in the Galactic star formation rate and density thresholds for star formation. *Mon. Not. R. Astron. Soc.* **2013**, *429*, 987–1000. [[CrossRef](#)]
59. Longmore, S.N.; Kruijssen, J.M.D.; Bally, J.; Ott, J.; Testi, L.; Rathborne, J.; Bastian, N.; Bressert, E.; Molinari, S.; Battersby, C.; et al. Candidate super star cluster progenitor gas clouds possibly triggered by close passage to Sgr A*. *Mon. Not. R. Astron. Soc.* **2013**, *433*, L15–L19. [[CrossRef](#)]

60. Longmore, S.N.; Kruijssen, J.M.D.; Bastian, N.; Bally, J.; Rathborne, J.; Testi, L.; Stolte, A.; Dale, J.; Bressert, E.; Alves, J. The Formation and Early Evolution of Young Massive Clusters. In *Protostars Planets VI*; University of Arizona Press: Tucson, Arizona, USA, 2014; pp. 291–314.
61. Kauffmann, J.; Pillai, T.; Zhang, Q. The Galactic Center Cloud G0.253+0.016: A Massive Dense Cloud with low Star Formation Potential. *Astrophys. J. Lett.* **2013**, *765*, L35. [[CrossRef](#)]
62. Johnston, K.G.; Beuther, H.; Linz, H.; Schmiedeke, A.; Ragan, S.E.; Henning, T. The dynamics and star-forming potential of the massive Galactic centre cloud G0.253+0.016. *Astron. Astrophys.* **2014**, *568*, A56. [[CrossRef](#)]
63. Rathborne, J.M.; Longmore, S.N.; Jackson, J.M.; Foster, J.B.; Contreras, Y.; Garay, G.; Testi, L.; Alves, J.F.; Bally, J.; Bastian, N.; et al. G0.253+0.016: A Centrally Condensed, High-mass Protocluster. *Astrophys. J.* **2014**, *786*, 140. [[CrossRef](#)]
64. Rathborne, J.M.; Longmore, S.N.; Jackson, J.M.; Alves, J.F.; Bally, J.; Bastian, N.; Contreras, Y.; Foster, J.B.; Garay, G.; Kruijssen, J.M.D.; et al. A Cluster in the Making: ALMA Reveals the Initial Conditions for High-mass Cluster Formation. *Astrophys. J.* **2015**, *802*, 125. [[CrossRef](#)]
65. Lu, X.; Zhang, Q.; Kauffmann, J.; Pillai, T.; Longmore, S.N.; Kruijssen, J.M.D.; Battersby, C.; Gu, Q. Deeply Embedded Protostellar Population in the 20 km s⁻¹ Cloud of the Central Molecular Zone. *Astrophys. J. Lett.* **2015**, *814*, L18. [[CrossRef](#)]
66. Lu, X.; Zhang, Q.; Kauffmann, J.; Pillai, T.; Longmore, S.N.; Kruijssen, J.M.D.; Battersby, C.; Liu, H.B.; Ginsburg, A.; Mills, E.A.C.; et al. The Molecular Gas Environment in the 20 km s⁻¹ Cloud in the Central Molecular Zone. *Astrophys. J.* **2017**, *839*, 1. [[CrossRef](#)]
67. Walker, D.L.; Longmore, S.N.; Bastian, N.; Kruijssen, J.M.D.; Rathborne, J.M.; Jackson, J.M.; Foster, J.B.; Contreras, Y. Tracing the conversion of gas into stars in Young Massive Cluster Progenitors. *Mon. Not. R. Astron. Soc.* **2015**, *449*, 715–725. [[CrossRef](#)]
68. Walker, D.L.; Longmore, S.N.; Bastian, N.; Kruijssen, J.M.D.; Rathborne, J.M.; Galván-Madrid, R.; Liu, H.B. Comparing young massive clusters and their progenitor clouds in the Milky Way. *Mon. Not. R. Astron. Soc.* **2016**, *457*, 4536–4545. [[CrossRef](#)]
69. Federrath, C.; Rathborne, J.M.; Longmore, S.N.; Kruijssen, J.M.D.; Bally, J.; Contreras, Y.; Crocker, R.M.; Garay, G.; Jackson, J.M.; Testi, L.; et al. The Link between Turbulence, Magnetic Fields, Filaments, and Star Formation in the Central Molecular Zone Cloud G0.253+0.016. *Astrophys. J.* **2016**, *832*, 143. [[CrossRef](#)]
70. Walker, D.L.; Longmore, S.N.; Zhang, Q.; Battersby, C.; Keto, E.; Kruijssen, J.M.D.; Ginsburg, A.; Lu, X.; Henshaw, J.D.; Kauffmann, J.; et al. Star formation in a high-pressure environment: An SMA view of the Galactic Centre dust ridge. *Mon. Not. R. Astron. Soc.* **2018**, *474*, 2373–2388. [[CrossRef](#)]
71. Jeffreson, S.M.R.; Kruijssen, J.M.D.; Krumholz, M.R.; Longmore, S.N. On the physical mechanisms governing the cloud lifecycle in the Central Molecular Zone of the Milky Way. *arXiv* **2018**, arXiv:1805.02655. [[CrossRef](#)]
72. Barnes, A.T.; Longmore, S.N.; Battersby, C.; Bally, J.; Kruijssen, J.M.D.; Henshaw, J.D.; Walker, D.L. Star formation rates and efficiencies in the Galactic Centre. *Mon. Not. R. Astron. Soc.* **2017**, *469*, 2263–2285. [[CrossRef](#)]
73. Krumholz, M.R.; Kruijssen, J.M.D. A dynamical model for the formation of gas rings and episodic starbursts near galactic centres. *Mon. Not. R. Astron. Soc.* **2015**, *453*, 739–757. [[CrossRef](#)]
74. Krumholz, M.R.; Kruijssen, J.M.D.; Crocker, R.M. A dynamical model for gas flows, star formation and nuclear winds in galactic centres. *Mon. Not. R. Astron. Soc.* **2017**, *466*, 1213–1233. [[CrossRef](#)]
75. Kruijssen, J.M.D.; Longmore, S.N.; Elmegreen, B.G.; Murray, N.; Bally, J.; Testi, L.; Kennicutt, R.C. What controls star formation in the central 500 pc of the Galaxy? *Mon. Not. R. Astron. Soc.* **2014**, *440*, 3370–3391. [[CrossRef](#)]
76. Kruijssen, J.M.D.; Longmore, S.N. An uncertainty principle for star formation—I. Why galactic star formation relations break down below a certain spatial scale. *Mon. Not. R. Astron. Soc.* **2014**, *439*, 3239–3252. [[CrossRef](#)]
77. Kruijssen, J.M.D. Towards a multi-scale understanding of the gas-star formation cycle in the Central Molecular Zone. In *The Multi-Messenger Astrophysics of the Galactic Centre*; IAU Symposium; Crocker, R.M., Longmore, S.N., Bicknell, G.V., Eds.; Cambridge University Press: Cambridge, UK, 2017; Volume 322, pp. 64–74.

