The Galactic Center: Feeding and Feedback in a Normal Galactic Nucleus
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L. O. Sjouwerman, C. C. Lang & J. Ott

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Sturm und Drang: The turbulent, magnetic tempest in the Galactic center

Brian C. Lacki

Jansky Fellow of the National Radio Astronomy Observatory
Institute for Advanced Study
1 Einstein Lane
Princeton, NJ 08540, USA
email: `brianlacki@ias.edu`

Abstract. The Galactic center central molecular zone (GCCMZ) bears similarities with extragalactic starburst regions, including a high supernova (SN) rate density. As in other starbursts like M82, the frequent SNe can heat the ISM until it is filled with a hot ($\sim 4 \times 10^7$ K) superwind. Furthermore, the random forcing from SNe stirs up the wind, powering Mach 1 turbulence. I argue that a turbulent dynamo explains the strong magnetic fields in starbursts, and I predict an average B $\sim$ 70 μG in the GCCMZ. I demonstrate how the SN driving of the ISM leads to equipartition between various pressure components in the ISM. The SN-heated wind escapes the center, but I show that it may be stopped in the Galactic halo. I propose that the Fermi bubbles are the wind's termination shock.

Starburst regions are characterized by high densities of star-formation and all of its accompanying phenomena, including supernovae. Nearly everything about these regions is extreme compared to the Milky Way: the total star-formation rates, the internal turbulent pressures, specific star-formation rates, and magnetic fields are all elevated (e.g., Lacki *et al.* 2010). The compactness of these regions, though, makes it very hard to understand the parsec-scale physics happening in them; for example, they cannot be resolved in γ-rays.

Close enough to be easily resolved, the Galactic center central molecular zone (GCCMZ; within 100 pc of the Galactic center) is sometimes described as a mini-starburst region. It is intermediate between the rest of the Milky Way disk and the starburst centers of spiral galaxies like NGC 253. The magnetic fields and cosmic ray (CR) densities are higher than in the outlying Milky Way throughout the GCCMZ, and there is evidence for outflows, as in starbursts (Crocker *et al.* 2011).

In these proceedings, I describe the connection between supernovae (SNe) and turbulence in these extreme regions, and implications for the interstellar medium (ISM). For a fuller discussion, see Lacki (2013a).

1. Supernovae and the ISM in starburst regions

SNe are an important source of feedback in star-forming galaxies. Their forcing of the ISM is largely *mechanical*, as the shock of an expanding supernova remnant (SNR) sweeps up ambient mass and accelerates it. This mechanical action has several effects: first, it heats material swept up in the SNRs. Second, the shock accelerates CRs, a process that appears to take $\sim$ 10% of the SN mechanical energy. The shock also compresses or generates magnetic fields. But most importantly, supernovae push the ISM around randomly and compressively. Thus, SNRs are a source of turbulent driving in the ISM.

Of course, SNe are not the only source of turbulence in starburst regions. Gas disks can be gravitationally unstable if their Toomre $\mathcal{Q} < 1$; disk instabilities may dominate turbulent driving in high-z galaxies (Genzel *et al.* 2008). But SNe are likely important in regions where there *is* active star-formation, including the inner GCCMZ. SNe impart vast amounts of energy into the ISM (10^{51} erg per SN). Particularly, SNe are one of the few ways of stirring up the *hot* ISM, which is completely transparent to radiation and often is not even gravitationally bound and therefore immune to disk instabilities. They also drive some turbulence in the cold ISM, although the coupling efficiency is probably smaller ($\sim$ 10% or less; Thornton *et al.* 1998).

Supernovae shape the very phase structure of the ISM. The Milky Way's ISM is traditionally described by the three phase model, with thermally stable cool (100 K) and warm (10^4 K) gas. Expanding SNRs excavate "holes" in the ISM filled with slowly cooling hot (10^6 K) gas. Each SNR reaches some maximum radius $R_{\rm max}$ set by either radiative evolution or pressure balance, and then takes one flow-crossing time to collapse. Then the filling factor is parameterized as $1 - e^{-Q}$:

$$Q = \rho_{\rm SN} \times (4/3)\pi R_{\rm max}^3 \times R_{\rm max}/\sqrt{P_{\rm ISM}/\rho_{\rm ISM}}. \tag{1.1}$$

Even in the Galaxy, the hot gas filling factor is large, $\sim 1/2$ (McKee & Ostriker 1977).

The ISM may actually be simpler in starburst regions. Because the average gas density is much higher, cooling is much more efficient. In particular, the Strömgren volumes of starbursts are small (Lacki 2013b). Virtually all of the mass is in cold $\rm H_2$, with little warm ISM present. Starbursts' ISM structure is determined by whether the supernova rate density $\rho_{\rm SN}$ is high enough to overcome the pressure. The SNRs win out in relatively "tame" starburst regions, resulting in a volume-filling phase of extremely hot (4×10^7 K in M82) but very low density plasma. This plasma's sound speed is far greater than the escape speed, and it explodes out of the central region as a starburst wind. The hot material is replenished by new SNe. Evidence for this hot phase in M82 includes detection of diffuse hard X-rays by *Chandra* (Strickland & Heckman 2009) and the rapid expansion of SNRs (Fenech *et al.* 2010). Thus, these regions are "hot" starbursts. The remaining ISM is in relatively isolated cold molecular clouds. But in the most extreme starburst regions, like those found in Arp 220's nuclei, SNRs cannot expand very far before being overwhelmed by the external pressure. In particular, SNRs become radiative very quickly in the dense molecular gas, so $R_{\rm max}$ is small. Nearly the entire volume is filled with turbulent, cold molecular gas: I call these "cold" starbursts.

It is unclear whether the GCCMZ has a "hot" or "cold" starburst ISM. The low star-formation rate implies few SNRs trying to excavate a large gas mass; this may favor a cold ISM. On the other hand, the X-ray evidence for keV plasma points to a hot superwind reminiscent of those in hot starbursts (e.g., Uchiyama *et al.* 2013).

2. The characteristic energy density of starburst ISMs

Supernovae input volumetric mechanical power at a rate $\dot{\varepsilon}_{\rm mech} = \dot{E}/V$ into the ISM. The ISM has a scale height h, which is the largest scale on which motions can be coherent, and a density $\rho_{\rm ISM}$. These quantities define a characteristic energy density:

$$\bar{U} = [\rho_{\rm ISM} \dot{\varepsilon}_{\rm mech}^2 h^2]^{1/3} \tag{2.1}$$

For the Galactic center region, this characteristic energy density is equal to $U_{\rm GCCMZ}/k_B = 2 \times 10^6$ K cm^{-3}, where I use a density appropriate for hot wind ($n_H = 0.01$ cm^{-3}). In fact, this is of order the typical energy density of several ISM components within the GCCMZ. Supernova driving naturally explains why equipartition holds in starbursts.

Hot wind pressure – Supernovae inject mass into the starburst ISM. This material is so hot that it escapes in one sound-crossing time. These are the assumptions of the Chevalier & Clegg (1985) model of starburst winds, which I follow. The full solution of this model has a density arising from the mass injected by SNe, $\dot{M} = 0.1\beta \times \mathrm{SFR}$ where $\beta \approx 2$ for an M82-like superwind. Then the temperature is $T \approx m_H \dot{E}/(k_B \dot{M})$ and equals 4×10^7 K. The density is roughly $\rho \approx 2\dot{M}^{3/2}/(\dot{E}^{1/2}\pi R^2_{\mathrm{GCCMZ}})$, and amounts to 0.02 electrons per cm^3 in the GCCMZ. The thermal energy density is then $\sim \bar{U}$.

Turbulent pressure – Turbulence dissipates in one flow-crossing time on the outer scale ℓ_{outer} at which motions are driven. Then $\bar{U}$ is nearly the turbulent energy density if $\ell_{\mathrm{outer}} = h$. The actual ℓ_{outer} may be given by R_{max}, the maximum size of SNRs before their pressure is equal to that of the ambient ISM. In the GCCMZ, I find R_{max} is 30 pc in the hot wind and 10 – 20 pc in cold molecular clouds. The turbulence speeds are $\sigma = [2\dot{\varepsilon}_{\mathrm{mech}}\ell_{\mathrm{outer}}/\rho_{\mathrm{ISM}}]^{1/3}$. The predicted σ in the hot wind is Mach $\sim$1: the thermal and turbulent energies share a power source and last for some kind of flow crossing time.

Are the turbulent energy densities in the hot wind and the cold molecular clouds comparable? We have:

$$\frac{U^{\mathrm{hot}}_{\mathrm{turb}}}{U^{\mathrm{cold}}_{\mathrm{turb}}} = \left(\frac{\rho_{\mathrm{hot}}}{\rho_{\mathrm{cold}}}\right)^{1/3} \left(\frac{\dot{\varepsilon}_{\mathrm{hot}}}{\dot{\varepsilon}_{\mathrm{cold}}}\right)^{2/3} \left(\frac{\ell_{\mathrm{hot}}}{\ell_{\mathrm{cold}}}\right)^{2/3} \tag{2.2}$$

At first glance, the great range in ρ might argue otherwise. But the SNe turbulent driving is likely less efficient in cold molecular clouds, because most of the mechanical power from SNRs is simply radiated away. In addition, ℓ_{outer} is probably smaller in the cold phase as R_{max} is smaller for radiative SNRs in dense material. These effects counteract the larger ρ in the cold phase, so that remarkably, $U^{\mathrm{hot}}_{\mathrm{turb}} \sim U^{\mathrm{cold}}_{\mathrm{turb}}$.

Turbulent magnetic fields – The random motions induced by turbulence twist and kneed the magnetic field lines embedded within the plasma. As a result, turbulence tends to bring magnetic fields towards equipartition with the kinetic energy: this is the turbulent dynamo. So as a first guess, we expect U_B to be near $\bar{U}$. Indeed, estimates of the magnetic field strength in the Galactic center ($\geqslant 50$ μG) support this idea.

I predict that turbulence in the hot wind generates equipartition magnetic field strengths of $B_{\mathrm{hot}} = \sqrt{8\pi U^{\mathrm{hot}}_{\mathrm{turb}}} \approx 70$ μG in the GCCMZ. In the cold molecular clouds, the predicted magnetic field strength is more uncertain due to the possible variations in outer scale and mechanical stirring efficiency. But, if turbulent energy density does not change much from one phase to another, the magnetic field strength is likewise similar. My best estimates for B_{cold} are 100 – 200 μG in the GCCMZ.

Cosmic ray pressure – The lifetime of CRs in the Galactic center region is set by an advection time, as the starburst wind blows them out. We again have a reservoir powered by supernova mechanical energy that resides for a flow crossing time. Hence, CR pressure tracks the other pressures *if* advection sets the CR lifetime.

The radiation and thermal HII region pressures are also in loose equipartition with these ISM components in the GCCMZ. This is explained as a coincidence between the greater luminosity in radiation and a much shorter energy residence time (the light crossing time and the thermal cooling time, respectively).

3. The wind's fate: the Fermi bubbles as wind bubbles?

If the GCCMZ is a hot starburst, then the plasma, after spraying out of the GCCMZ, escapes with a terminal velocity of $v_\infty = \sqrt{2\dot{E}/\dot{M}} \approx 1600\ \mathrm{km\,s^{-1}}$. Yet such a wind cannot continue forever. As it expands to larger radii, its ram pressure decreases. Eventually, it is no bigger than the external pressure in the Galactic halo, which is $\sim 10^3$ K cm^{-3} (Savage *et al.* 2003). At this point it reaches a termination shock, heating the adiabatically-cooled gas. More interestingly, wind termination shocks may be sites of CR acceleration (c.f., Jokipii & Morfill 1987); freshly accelerated electrons would be visible in synchrotron radio and Inverse Compton γ-rays. The termination shock for a GCCMZ wind expanding into a solid angle $\Omega \approx \pi$ is

$$R_t \approx \sqrt{\dot{M} v_\infty / (2 \Omega P_{\rm halo})} \approx 5 \text{ kpc}. \tag{3.1}$$

Interestingly, this is of order the size of the Fermi bubbles (Su *et al.* 2010). The bubbles have a dynamical time $R_t / \sqrt{P_{\rm halo}/\rho_{\rm halo}}$ of ~ 40 Myr if the wind shuts off.

The most spectacular interpretation is that the Fermi bubbles actually are the wind termination shock (Lacki 2013c). The bubbles' γ-ray luminosity is, to order of magnitude, consistent with the mechanical luminosity of SNe, after assuming 30% CR acceleration efficiency and 1/40 of the CR power going into electrons. But if the GCCMZ has been forming stars for $\gg 10$ Myr, and if the bubbles are wind bubbles, then there should be old electrons surrounding the bubbles visible at low radio frequencies.

More subtly, the wind bubble from the GCCMZ represent initial conditions for any AGN jet launched from Sgr A* itself. If the hot wind exists, the jet first burrows through the wind bubble associated with the mini-starburst before reaching the halo. This may affect scenarios where the Fermi bubbles are associated with Sgr A*.

In this picture, the energy of supernovae is converted back and forth between heat and bulk motion: the ISM acts like a series of pistons within pistons. An expanding SNR stirs up the ISM, converting its bulk motion into random turbulent motion. This energy dissipates into heat, creating a hot ISM. But the pressure outside the GCCMZ is much lower, so the hot ISM itself expands furiously, converting the heat energy back into bulk kinetic energy as a wind. Finally, at the termination shock, the bulk kinetic energy is randomized into CRs and heat once again.

Acknowledgements

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