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STEADY-STATE HADRONIC GAMMA-RAY EMISSION FROM 100-MYR-OLD FERMI BUBBLES

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ABSTRACT

Fermi Bubbles are enigmatic γ-ray features of the Galactic bulge. Both putative activity (within few × Myr) connected to the Galactic center super-massive black hole and, alternatively, nuclear star formation have been claimed as the energizing source of the Bubbles. Likewise, both inverse-Compton emission by non-thermal electrons ("leptonic" models) and collisions between non-thermal protons and gas ("hadronic" models) have been advanced as the process supplying the Bubbles' γ-ray emission. An issue for any steady state hadronic model is that the very low density of the Bubbles' plasma seems to require that they accumulate protons over a multi-gigayear timescale, much longer than other natural timescales occurring in the problem. Here we present a mechanism wherein the timescale for generating the Bubbles' γ-ray emission via hadronic processes is ∼few $\times 10^8$ yr. Our model invokes the collapse of the Bubbles' thermally unstable plasma, leading to an accumulation of cosmic rays and magnetic field into localized, warm ($\sim 10^4$ K), and likely filamentary condensations of higher-density gas. Under the condition that these filaments are supported by non-thermal pressure, the hadronic emission from the Bubbles is $L_\gamma \simeq 2 \times 10^{37}$ erg s^{-1} $\dot{M}_{\rm in}/(0.1\,M_\odot$ yr$^{-1})$ $T_{\rm FB}^2/(3.5 \times 10^7$ K$)^2$ $M_{\rm fil}/M_{\rm pls}$, equal to their observed luminosity (normalizing to the star-formation-driven mass flux into the Bubbles and their measured plasma temperature and adopting the further result that the mass in the filaments, $M_{\rm fil}$ is approximately equal to the that of the Bubbles' plasma, $M_{\rm pls}$).

Key words: cosmic rays – gamma rays: diffuse background

1. INTRODUCTION

The Fermi Bubbles (Dobler et al. 2010; Su et al. 2010) are giant 1–100 GeV γ-ray structures that extend ∼7 kpc north and south of the Galactic nucleus. Structures roughly coincident with the Bubbles are known in X-rays (Bland-Hawthorn & Cohen 2003), total intensity microwaves (Finkbeiner 2004; Dobler & Finkbeiner 2008; Dobler 2012; Ade et al. 2013), polarized intensity microwaves (Jones et al. 2012), and polarized intensity radio continuum (Carretti et al. 2013) emission.

Much theoretical work on the Bubbles has focused on the idea that their γ-ray emission is supplied by the inverse-Compton (IC) up-scattering of ambient light by a cosmic ray (CR) electron population. Given that the Bubbles extend so far into the halo with a relatively fixed hard spectrum, an IC model must invoke up-scattering of the cosmic microwave background to multi-GeV gamma-ray energies, requiring $\gtrsim$ TeV electron primaries. Such electrons cool quickly, defining a natural timescale $\lesssim$1 Myr. To explain, then, the large extent and energy content of the Bubbles, some models (e.g., Zubovas & Nayakshin 2012; Guo & Mathews 2012; Yang et al. 2012, 2013; Barkov & Bosch-Ramon 2013) hypothesize recent activity of the super-massive black hole at the Galactic Center (GC) with very fast transport of the electrons. These timing constraints are relaxed if there is distributed acceleration (Cheng et al. 2011; Mertsch & Sarkar 2011; Lacki 2013) throughout the structures. Evidence in support of an active galactic nucleus-like scenario may come from the detection (Su & Finkbeiner 2012) of a jet-like feature in the γ-ray data and the recent claim that the Magellanic stream was bathed in a bright UV flash only a few million years ago (Bland-Hawthorn et al. 2013).

Alternatively, the Bubbles' γ-ray emission may be hadronic in origin with CR protons (and heavier ions)—ultimately energized by nuclear star-formation—accumulated over (much) longer timescales, colliding with ambient gas to supply the γ-rays (Crocker & Aharonian 2011). A number of pieces of evidence are consistent with this scenario. First, the intense star-formation in the inner ∼200 pc diameter region around the GC *currently* produces a CR power that is elegantly sufficient to supply both the (hadronic) γ-ray luminosity of the Bubbles (Crocker et al. 2011; Crocker 2012) and the 2.3 GHz synchrotron luminosity of the recently discovered, polarized radio lobe counterparts to the Bubbles (Carretti et al. 2013). Second, as we show below (also see Crocker 2012), the mass flux of $\sim 0.1\,M_\odot$ yr^{-1} from the nuclear-star-formation-driven outflow is elegantly sufficient to maintain the Bubbles' plasma mass in steady-state against its thermal losses. Last and more speculatively, in the sky distribution of up to 28 neutrino events recently observed by IceCube against a background of 10.6 atmospheric events, there is a hint of an overabundance of neutrinos from the direction of the Inner Galaxy with an inferred flux consistent with a hadronic origin for the γ-rays (Aartsen et al. 2013; Ahlers & Murase 2013; Razzaque 2013).

The apparent cost, however, of any steady state hadronic model is the long timescale implied. The protons and ions fed into the Bubbles collide with ambient gas nuclei over the *pp* loss time which, on the low volumetric average gas density, is $t_{\rm pp} \simeq 10$ Gyr $[n_{\rm H}/(0.005$ cm$^{-3})]^{-1}$. Establishing a steady state requires that the structures have existed for this sort of timeframe, which is difficult to reconcile with other natural timescales relating to the Bubbles/GC. In particular, the 2.3 GHz polarization observations (Carretti et al. 2013) suggest that the outflow feeding electrons into the radio lobes has a vertical speed of ∼1100 km s^{-1} giving an advective timescale over the ∼8 kpc extent of the radio lobes (marginally larger than the Bubbles) of

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only 7×10^6 yr. Nuclear star-formation, which supplies a total mechanical power of $\sim 3 \times 10^{40}$ erg s^{-1}, ~80% of which goes into heating or moving the outflowing plasma (Crocker 2012), cannot supply all the Bubbles' energy ($\gtrsim 5 \times 10^{55}$ erg) within this timescale.

We show immediately below, however, that both this short advection timescale and the long timescale associated with steady-state hadronic emission need to be reconsidered, given the natural mechanism that is the subject of this Letter. Briefly, we discuss the following: cooling of the Bubbles' interior plasma over $1\text{–}2 \times 10^8$ yr into cool, overdense filaments leads to the adiabatic compression of CRs and magnetic fields. With the simple prescription that the (dominantly non-thermal) pressure of the filaments reaches equilibrium with the Bubble plasma, we can predict their hadronic emission. As we show below, this prediction is a good match to observations

2. TIMESCALES RECONSIDERED

The ~ 1100 km s^{-1} characteristic speed at the base of the outflow is suggested by two independent analyses of the radio data based on (1) a geometrical analysis of the curvature of one of the strongly magnetized linear "ridge" features seen in the data, and (2) the cooling time of the electrons whose synchrotron emission reaches to the top of the radio lobes. This speed is somewhat in excess of the gravitational escape velocity (~ 900 km s^{-1}; Muno et al. 2004), and, if interpreted as purely a plasma velocity, is expected to imply an escaping wind.

In fact, however, the fast flow *does not escape to infinity*: the 23 GHz polarization data show that the magnetic field lines curl over toward horizontal at the top of the Bubbles, suggesting a vertical speed that is significantly slowing. Thus, there is a structure of a definite, finite height, not a freely expanding wind. The CRs stream ahead of the plasma with a speed limited to the Alfvén velocity because of the streaming instability. This velocity also controls the speed with which torsional Alfvén waves respond to the driving from the rotation of the outflow's base. We thus re-interpret the previously determined 1100 km s^{-1} characteristic speed as the sum of two components: a plasma wind speed *that is somewhat less than the escape velocity* (but still capable of delivering gas to ~few kiloparsec heights into the halo) and the Alfvén speed along the magnetic field lines. Thus, material and energy can be accumulated into the Bubbles for significantly longer than 7×10^6 yr.

The second problem is to reconcile the very long hadronic timescale with other timescales. For instance, the thermally unstable Bubble plasma cools over $(1\text{–}2) \times 10^8$ yr (see below), collapsing into overdense condensations. This concentrates the magnetic field attached to the plasma, thereby mustering in the CRs. Analogous to the processes occurring around the brightest central galaxies (BCGs) of clusters (Sharma et al. 2010), this collapse will continue until the non-thermal pressure in the condensations equilibrates with the external plasma pressure. The CRs and magnetic fields evolve adiabatically at the beginning of the collapse, in contrast to the plasma whose collisional losses rise strongly as n^2. Thus, the non-thermal interstellar medium phases come to dominate the pressure in the condensations despite their softer equations of state. As for the Hα filaments around BCGs (Sharma et al. 2010), anisotropic heat conduction (due to the suppression of electron motions transverse to magnetic fields) means that the condensations assume the topology of extended filaments with dominantly longitudinal magnetic fields. With this picture, we can calculate how the collapse proceeds.

3. HADRONIC EMISSION FROM COOLING FILAMENTS

The Milky Way has an X-ray bulge (XRB) with some individual features clearly correlated with Bubble structures (Su et al. 2010). The *bolometric* thermal luminosity of the XRB lies in the range $L_{\rm XRB} = (3\text{–}9) \times 10^{39}$ erg s^{-1} (Snowden et al. 1997; Almy et al. 2000). From this luminosity and assuming a static structure, we can calculate the rate at which material is cooling out of the XRB as $\dot{M}_{\rm cool} \simeq 2/3\, L_{\rm XRB}\, \mu m_{\rm p}/(k_{\rm B} T) \sim (0.07\text{–}0.2)\, M_\odot$ yr^{-1} ($\mu \simeq 0.6$ is the mean mass of the plasma constituents in terms of $m_{\rm p}$). This $\dot{M}_{\rm cool}$ is close to the mass efflux (Crocker 2012) along the SF-driven nuclear outflow. Given that the mechanical energy *and* mass injected by nuclear SF can sustain the non-thermal luminosity of the Bubbles in steady state, we postulate that the Bubbles are enduring structures inflated and sustained by nuclear star formation. In this circumstance, freshly injected plasma from the nuclear outflow balances the mass drop-out rate, $\dot{M}_{\rm in} \equiv \dot{M}_{\rm cool}$, resulting in a steady state gas density in the Bubbles of

$$n_{\rm H^+}^{\rm FB} = \left(\frac{\dot{M}_{\rm in}\; T_{\rm FB}\; k_{\rm B}}{(\gamma - 1)\, \mu\; 1.22\, m_{\rm p}\; V_{\rm FB}\; \Lambda[T]} \right)^{1/2} \simeq 0.003 \text{ cm}^{-3} \left(\frac{\dot{M}_{\rm in}}{0.1\, M_\odot \text{ yr}^{-1}} \right)^{1/2}, \quad (1)$$

where $n_{\rm e} \simeq 1.22 n_{\rm H^+}$, $(\gamma - 1) = 2/3$, $\Lambda[T]$ is the plasma thermal cooling function (Raymond et al. 1976), and $V_{\rm FB} = 8.4 \times 10^{66}$ cm^3. Reinforcing the steady state picture, this $n_{\rm H^+}^{\rm FB}$ estimate is consistent with X-ray measurements by *Suzaku* (Kataoka et al. 2013) which give $T_{\rm FB} \simeq 3.5 \times 10^6$ K for the Bubble plasma (equal to that of the adjacent halo plasma) and from which we infer $n_{\rm H^+}^{\rm FB} \simeq (1\text{–}3) \times 10^{-3}$ cm^{-3}.

For this plasma number density and temperature the cooling time is $(1\text{–}2) \times 10^8$ yr. We show below that the timescale for the formation of the Bubbles is $\gtrsim 2 \times 10^8$ yr, only a little longer.

Given the adiabatic compression of relativistic CR protons into the plasma condensations, we can make an estimate of the hadronic γ-ray emission from the Bubbles, finding consistency with observations. The filament pressure, supplied by relativistic CR protons (denoted by p) and magnetic fields (B), equilibrates with the external plasma pressure, $p^{\rm fil} \equiv p_{\rm p}^{\rm fil} + p_B^{\rm fil} = p^{\rm FB} = 2.2 \times T_{\rm FB}\, k_{\rm B}\, n_{\rm H^+}^{\rm FB} = 2.0$ eV cm^{-3} and we suppose $p_{\rm p}^{\rm fil} \simeq p_B^{\rm fil}$. The energy density of the adiabatically accumulated, relativistic CR protons in the filaments is $u_p^{\rm fil} = u_p^{\rm GC} (n_{\rm H}^{\rm fil}/n_{\rm H}^{\rm GC})^{4/3}$, where GC denotes a parameter of the nuclear star formation region where the CRs and thermal plasma are energized. With $p_p^{\rm fil} \equiv 1/3\; u_p^{\rm fil} = 1/2\; p^{\rm fil}$, we determine the filament filling factor as $f = (3.3\; k_{\rm B}\; T_{\rm FB} n_{\rm H^+}^{\rm FB}/u_p^{\rm GC})^{3/4}\; n_{\rm H^+}^{\rm FB}/n_{\rm H^+}^{\rm GC}$ and the hadronic luminosity from 1 to 100 GeV of the filaments is

$$L_\gamma^{\rm pp} \simeq 3/2\; 1/3\; f_{\rm bolo}\, \sigma_{\rm pp}\, \kappa_{\rm pp}\, c\; n_{\rm H}^{\rm fil}\; u_{\rm p}^{\rm fil}\; \; V_{\rm fil} \simeq \frac{3\; f_{\rm bolo}\, \sigma_{\rm pp}\, \kappa_{\rm pp}\, c\; \dot{M}_{\rm in} (k_{\rm B}\; T_{\rm FB})^2}{\Lambda[T_{\rm FB}]\, m_{\rm p}} \left(\frac{M_{\rm fil}}{M_{\rm pls}} \right) \simeq 2 \times 10^{37} \text{ erg s}^{-1} \left(\frac{\dot{M}_{\rm in}}{0.1\, M_\odot \text{ yr}^{-1}} \right) \left(\frac{T_{\rm FB}}{3.5 \times 10^6 \text{ K}} \right)^2 \left(\frac{M_{\rm fil}}{M_{\rm pls}} \right), \quad (2)$$

where $\kappa_{\rm pp} \simeq 0.5$ is the inelasticity of pp collisions, a factor of 3/2 corrects for the presence of heavy ions (Mori 1997), 1/3 comes from the relative multiplicity of π^0 amongst all daughter pions, and $f_{\rm bolo} \simeq 0.4$ is the fraction of the bolometric luminosity emitted in the 1–100 GeV range. (As in the original hadronic model of Crocker & Aharonian 2011, this scenario reproduces the Bubbles' hard spectrum given the energy independence of the relevant transport processes and near energy independence of $\sigma_{\rm pp}$ above the kinematic threshold.) Thus, normalizing to the measured plasma temperature and the mass injection rate required to maintain its density in steady state (Equation (1)), the expected luminosity matches that observed (Lunardini & Razzaque 2012) *provided* that the filaments' integrated mass, $M_{\rm fil}$, approximately equals that in the plasma $M_{\rm pls}(\simeq 2 \times 10^7\, M_\odot)$.

Remarkably, this condition is met: given the steady state, we have $M_{\rm fil}/M_{\rm pls} \equiv \langle t_{\rm fall}\rangle / t_{\rm cool}$ with $\langle t_{\rm fall}\rangle$ the mean time for the filaments to fall to the plane *at their terminal speed* (cf. Benjamin & Danly 1997) through the Bubble plasma of density $\rho_{\rm pls}$. For a horizontally aligned filament, this is given by

$$v_{\rm term}^{\rm horiz}[r,z] \simeq \left(\frac{\pi}{2}\frac{\rho_{\rm fil}}{\rho_{\rm pls}}\frac{r_{\rm fil}\, g[r,z]}{c_D}\right)^{1/2}, \quad (3)$$

where $g[r,z]$ is the magnitude of the gravitational acceleration at $\{r,z\}$ and c_D is the drag coefficient (for a vertically aligned filament of length $L_{\rm fil}$, replace $\pi/2\ r_{\rm fil} \to L_{\rm fil}$). The filament terminal velocity is super-Alfvénic through the Bubble plasma; this implies draping of the Bubbles' magnetic field around the filaments, the formation of magnetic wakes behind the filaments, and a consequent increase in drag with respect to the hydrodynamic expectation that is accounted for by setting $c_D \simeq 1.9$, which we adopt here (Dursi & Pfrommer 2008). Employing the potential described by Breitschwerdt et al. (1991), we find the mean time for the filaments to fall from their condensation sites at $z_{\rm launch}$ to the plane at the terminal speed to be $t_{\rm fall}[z] \simeq 8 \times 10^7\ (z_{\rm launch}/4\ {\rm kpc})^{0.7}$ yr. Accounting for the fact that filaments do not form below ∼3 kpc (see below), we find that the mean filament falling time satisfies $\langle t_{\rm fall}\rangle \sim t_{\rm cool}$ to better than a factor 2. This agreement is not accidental but essentially guaranteed by the following considerations: While buoyancy effects mean that a hot, gravitationally confined, and stratified atmosphere is *not* generally susceptible to the local cooling instability (Balbus & Soker 1989; Binney et al. 2009), it has been empirically and theoretically established (McCourt et al. 2012; Sharma et al. 2012; Li & Bryan 2014) that cooling filaments *can* form within a medium in global thermal balance wherever the ratio of the cooling to the *free* fall time, $t_{\rm ff}$, satisfies $t_{\rm cool}/t_{\rm ff} < (3\text{–}10)$, particularly if the medium is subject to external perturbations. This timescale ratio condition is satisfied in the Bubbles for $z \gtrsim 3$ kpc. Thus, because $t_{\rm fall} \sim$ few $\times\ t_{\rm ff}$, we automatically have $t_{\rm cool}/t_{\rm fall} \lesssim$ few in any environment where filaments form.

4. DISCUSSION

At equilibrium the filaments are compressed to $f \sim 10\%$ and $n_H^{\rm fil} \sim 0.03\ {\rm cm}^{-3}$. At any given filament $n_{\rm H^+}$, we require that the filaments are warm enough to obey the (conservative) Hα intensity upper limit ∼0.3 Rayleigh (Finkbeiner 2004); this condition means that the filament gas must be warmer than ∼5000 K. At this temperature, their cooling rate is 3×10^{39} erg s^{-1}, ∼10% of the mechanical energy injected into the nuclear outflow. The filament temperature may thus be maintained by an internal agent associated with the outflow—shock heating, thermal conduction, dissipation of hydrodynamical turbulence, magnetic field reconnection, and/or CR excitation of MHD waves or direct CR ionisation—or an external one, e.g., photoionization heating from Lyman continuum photons supplied by the young nuclear stars.

The filament filling factor we favor, ∼10%, corresponds to a layer of thickness ∼100 pc if distributed evenly over the (assumed) spherical volume of each bubble. The compressed magnetic field amplitude is expected to be $\sim 10\,\mu$G. These numbers are a near match to the depth (200–300 pc) and amplitude ($\sim 10\,\mu$G) for the magnetized sheath suggested to cover the Bubbles by Carretti et al. (2013).

Within our model, CRs are initially distributed throughout the volume of the Bubbles and are subsequently gathered in to the filaments by the collapse of the thermally unstable plasma. This process requires that the inward convective velocity exceeds the effective outward velocity associated with CRs' lateral escape. Because the filaments' field lines are largely longitudinal, lateral escape is via cross-field diffusion or, more importantly, field line wandering (Jokipii & Parker 1969). In either case, lateral escape is generically much slower than diffusion *along* the filaments, which is diffusive with the diffusion coefficient $D_{||}$, but limited to the Alfvén velocity because of the streaming instability. In the case of field line wandering, the expectation value of the square of the perpendicular distance reached in time t is given by $\langle r^2\rangle = 4\ D_M \sqrt{2\ D_{||}\ t}$ (Nava & Gabici 2013). D_M, the diffusion coefficient for the field lines (with dimensions of length), is poorly constrained. If we adopt $D_M = 1$ pc from Nava & Gabici (2013) and a parallel diffusion coefficient $D_{||}$ similar to that of the Galactic plane, we determine that CR protons up to an energy ∼1 TeV are trapped within the filaments over the $\sim 10^8$ yr cooling time if their inward transversal collapse (down to final radius r_f) proceeds at $\sim \sqrt{f}\ r_f/t_{\rm cool} \sim 3$ km s^{-1} $r_f/(100\ {\rm pc})\ (t_{\rm cool}/(10^8\ {\rm yr})^{-1}$. With these parameter choices, higher-energy CR protons start to escape the filaments within the cooling timescale; consistent with this, there is a steepening in the Bubbles' γ-ray spectrum at ∼100 GeV, corresponding to primary protons of energy ∼1 TeV.

We suggest an intimate connection between the Bubbles and the nuclear molecular torus, which is fed by the Galactic bar and akin to nuclear star-forming rings found in other barred spirals. The torus constitutes much of the mass of the central molecular zone (Molinari et al. 2011) and, with a gravitational potential energy of few $\times 10^{56}$ erg, it is the logical candidate to anchor the Bubbles' field lines. The natural timescale associated with the formation of the torus is also $\gtrsim 10^8$ yr, over which it has hosted the formation of $\sim 10^7\ M_\odot$ of stars and consequently $\sim 10^5$ core-collapse supernovae that have released $\sim 10^{56}$ erg mechanical energy. The torus seems (Zubovas & Nayakshin 2012; Crocker 2012), moreover, to collimate the GC outflow and material ablated off its inner edge can naturally supply the H I clouds recently detected (McClure-Griffiths et al. 2013) at relatively low latitudes, $|b| < 5^\circ$, entrained into a nuclear outflow. These $n_{\rm HI} \sim 1\ {\rm cm}^{-3}$ clouds will help nucleate the condensation of plasma (Marinacci et al. 2010), especially toward the edges of the Bubbles. To match their flat γ-ray surface brightness, a volumetric emissivity that strongly peaks toward the edges of the Bubbles is required (Su et al. 2010); filament nucleation occurring preferentially near the edges may achieve this.

Direct evidence for warm, ionized gas with characteristics very similar to those we infer for the filaments has been obtained via UV absorption studies (Keeney et al. 2006; Zech et al. 2008). These works have uncovered warm, ionized gas clouds high above and below the GC with number densities $\lesssim$few $\times$ 0.1 cm^{-3} and temperatures in the range few $\times 10^4$ K. These clouds have insufficient velocity to escape the Galaxy and are thus participating in a nuclear fountain. Tantalizingly, all the sight lines that reveal fountaining warm plasma are within the solid angle of the Bubbles or the somewhat larger radio lobes. Of particular interest, the sightline to the Messier 5 globular cluster (Zech et al. 2008) passes very close to the edge of the north Bubble and reveals super-solar metallicity ($\sim$1.6 $Z_\odot$) fountain material, consistent with the scenario of filament nucleation occurring preferentially toward the Bubble edges.

While we believe that nuclear star formation ultimately powers the Bubbles, the mechanism of CR hadron accumulation into cooling filaments does not necessarily require that the CRs are accelerated (only) in the nucleus. They may, for instance, be (re)accelerated on significantly larger scales by shocks in the outflow (cf. Lacki 2013). Indeed, our analysis would still hold in the case that an outburst from Sgr A* $\gtrsim 10^8$ yr ago inflated the Bubbles. Regardless, the fountaining-back of relatively cool and low angular momentum filament gas to the plane may occasionally provide a cold accretion flow on to the black hole or fuel star-formation very close to it.

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REFERENCES

Aartsen, M. G., Abbasi, R., Abdou, Y., et al. 2013, PhRvRL, 111, 021103
Ahlers, M., & Murase, K. 2013, arXiv:1309.4077
Almy, R. C., McCammon, D., Digel, S. W., Bronfman, L., & May, J. 2000, ApJ, 545, 290
Balbus, S. A., & Soker, N. 1989, ApJ, 341, 611
Barkov, M. V., & Bosch-Ramon, V. 2013, A&A, 565, A65
Benjamin, R. A., & Danly, L. 1997, ApJ, 481, 764
Binney, J., Nipoti, C., & Fraternali, F. 2009, MNRAS, 397, 1804
Bland-Hawthorn, J., & Cohen, M. 2003, ApJ, 582, 246
Bland-Hawthorn, J., Maloney, P. R., Sutherland, R. S., & Madsen, G. J. 2013, ApJ, 778, 58
Breitschwerdt, D., McKenzie, J. F., & Voelk, H. J. 1991, A&A, 245, 79
Carretti, E., Crocker, R. M., Staveley-Smith, L., et al. 2013, Natur, 493, 66
Cheng, K.-S., Chernyshov, D. O., Dogiel, V. A., Ko, C.-M., & Ip, W.-H. 2011, ApJL, 731, L17
Crocker, R. M. 2012, MNRAS, 423, 3512
Crocker, R. M., & Aharonian, F. 2011, PhRvL, 106, 101102
Crocker, R. M., Jones, D. I., Aharonian, F., et al. 2011, MNRAS, 413, 763
Dobler, G. 2012, ApJ, 750, 17
Dobler, G., & Finkbeiner, D. P. 2008, ApJ, 680, 1222
Dobler, G., Finkbeiner, D. P., Cholis, I., Slatyer, T., & Weiner, N. 2010, ApJ, 717, 825
Dursi, L. J., & Pfrommer, C. 2008, ApJ, 677, 993
Finkbeiner, D. P. 2004, ApJ, 614, 186
Guo, F., & Mathews, W. G. 2012, ApJ, 756, 181
Jokipii, J. R., & Parker, E. N. 1969, ApJ, 155, 777
Jones, D. I., Crocker, R. M., Reich, W., Ott, J., & Aharonian, F. A. 2012, ApJL, 747, L12
Kataoka, J., Tahara, M., Totani, T., et al. 2013, ApJ, 779, 57
Keeney, B. A., Danforth, C. W., Stocke, J. T., et al. 2006, ApJ, 646, 951
Lacki, B. C. 2013, arXiv:1304.6137
Li, Y., & Bryan, G. L. 2014, ApJ, 789, 153
Lunardini, C., & Razzaque, S. 2012, PhRvL, 108, 221102
Marinacci, F., Binney, J., Fraternali, F., et al. 2010, MNRAS, 404, 1464
McClure-Griffiths, N. M., Green, J. A., Hill, A. S., et al. 2013, ApJL, 770, L4
McCourt, M., Sharma, P., Quataert, E., & Parrish, I. J. 2012, MNRAS, 419, 3319
Mertsch, P., & Sarkar, S. 2011, PhRvL, 107, 091101
Molinari, S., Bally, J., Noriega-Crespo, A., et al. 2011, ApJL, 735, L33
Mori, M. 1997, ApJ, 478, 225
Muno, M. P., Baganoff, F. K., Bautz, M. W., et al. 2004, ApJ, 613, 326
Nava, L., & Gabici, S. 2013, MNRAS, 429, 1643
Planck Collaboration, Ade, P. A. R., Aghanim, N., Arnaud, M., et al. 2013, A&A, 554, A139
Raymond, J. C., Cox, D. P., & Smith, B. W. 1976, ApJ, 204, 290
Razzaque, S. 2013, PhRvD, 88, 081302
Sharma, P., McCourt, M., Quataert, E., & Parrish, I. J. 2012, MNRAS, 420, 3174
Sharma, P., Parrish, I. J., & Quataert, E. 2010, ApJ, 720, 652
Snowden, S. L., Egger, R., Freyberg, M. J., et al. 1997, ApJ, 485, 125
Su, M., & Finkbeiner, D. P. 2012, ApJ, 753, 61
Su, M., Slatyer, T. R., & Finkbeiner, D. P. 2010, ApJ, 724, 1044
Yang, H.-Y. K., Ruszkowski, M., Ricker, P. M., Zweibel, E., & Lee, D. 2012, ApJ, 761, 185
Yang, H.-Y. K., Ruszkowski, M., & Zweibel, E. 2013, MNRAS, 436, 2734
Zech, W. F., Lehner, N., Howk, J. C., et al. 2008, ApJ, 679, 460
Zubovas, K., & Nayakshin, S. 2012, MNRAS, 424, 666