Mem. S.A.It. Vol. 83, 117
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Memorie della

Fermi bubbles: Galactic centre star formation writ large

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Abstract. The enormous ∼GeV γ-ray emitting structures recently discovered in *Fermi*-LAT data and labelled the 'Fermi Bubbles' are, given their north-symmetry around the Galactic plane and the fact that they are emerge from the Galactic centre (GC), are related to the high-energy activity in the Milky Way nucleus. Here I show that these structures are likely related to the sustained, long-duration star-formation processes that have occurred in the GC since the youth of the Galaxy. In particular, our independent modelling of the inner ∼200 pc of the Galaxy – directed at explaining the diffuse, broad-band (radio continuum to TeV γ-ray), non-thermal signal detected from this region – demonstrates that a super-wind type outflow from the GC advects $\sim 10^{39}$ erg/s in cosmic ray protons into the Galactic halo, precisely enough to energise the γ-ray emission from the Fermi Bubbles.

Key words. cosmic rays – galaxies: star formation – Galaxy: center – ISM: jets and outflows – ISM: supernova remnants – radiation mechanisms: non-thermal

1. Introduction

Recently NASA announced the startling discovery (Dobler et al. 2010; Su et al. 2010) by *Fermi* of two enormous gamma-ray emission structures that hang like lightglobes above and below the centre of the Milky Way. These 'Fermi bubbles' extend an astounding 10 kpc from the plane of the Galaxy. At lower Galactic latitudes these structures are coincident with a non-thermal microwave 'haze' found in WMAP 20-60 GHz data (Finkbeiner et al. 2004; Dobler & Finkbeiner 2008) and an extended region of diffuse X-ray emission detected by ROSAT (Snowden et. al. 1997). Thus far the Bubbles have been typically understood as illuminated by a mysterious population of youthful and highly energetic (∼TeV) electrons of age 10 million years or so which simultaneously inverse-Compton radiate (off the CMB) at ∼GeV energies and synchrotron radiate at microwave frequencies. However, given the severe radiative energy losses experienced by electrons, the hard spectrum, uniform intensity, vast extension, and energetics of the bubbles render the origin of this particle population extremely mysterious (Finkbeiner et al. 2004; Dobler & Finkbeiner 2008; Dobler et al. 2010; McQuinn & Zaldarriaga 2010; Su et al. 2010). In particular, even accounting only for energy losses on the CMB, transport of ≥TeV, IC-radiating electrons to the requisite distances from the plane would require velocities of $> 0.03\ c$, too fast for a Galactic wind (though an AGN jet potentially offers a suitable

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delivery mechanism in this connection: Guo & Mathews 2011). Below I will demonstrate that a compelling alternative explanation for the origin of the Bubbles is a hadronic one where CR protons (and heavier ions) accelerated in the inner $\sim$ 100 pc (in radius) of the Galaxy and carried out of the plane on a 'super-wind' provide the power to illuminate the Bubbles.

2. Galactic centre as starburst analogue

The Galactic centre (GC) provides an interesting, potential analogue to the nucleus of a luminous star-burst galaxy. Indeed, the ISM conditions prevailing in the inner $\sim$ 100 pc (in radius) of the Galaxy – the region under consideration here – render it arguably more akin to the environs of a star-burst than than to the relatively quiescent conditions of the Galactic disk. In particular, the GC contains something like 5% of the Galaxy's molecular hydrogen allocation (Morris & Serabyn 1996) implying a very high, volumetric-average gas density in the region. Moreover, the energy-densities of the various GC ISM components are 1–2 orders of magnitude larger than those found locally, as is the areal density of star-formation and attendant supernova activity. For instance, as we have recently shown (Crocker et al. 2010a), the GC is threaded by a remarkably strong magnetic field of $\sim$100 μG (cf. with $\sim$5 μG for the Galactic disk).

In recent years a picture has begun to emerge that the inner regions of star-forming galaxies should i) be important sources of γ-rays in the universe (Pavlidou & Fields 2002; Thompson et al. 2007; Dogiel & Breitschwerdt 2009); ii) drive powerful galactic winds (Dogiel & Breitschwerdt 2009) and iii) therefore, be important shapers of the intergalactic medium, particularly its metallicity (Strickland & Heckman 2009). Interestingly, recent observations reveal that GC is a significant γ-ray source exhibiting both point-like GeV (Chernyakova et al. 2011) and TeV (Aharonian et al. 2004) emission coincident with Sagittarius A* (at the dynamical centre of the Galaxy and most associated with the supermassive black hole found there) and diffuse emission also at both GeV (Digel et al. 2009) and TeV (Aharonian et al. 2006) energies.

We argue here for a further similarity to star-bursts: many direct observations (see Appendix C of (Crocker et al. 2011b) and references therein) and, in addition, the non-thermal evidence reviewed below point to the existence of a power outflow or wind of at least a few 100 km/s out of the GC.

3. Broad-band modelling of the Galactic centre

We have created a 1-zone model of the injection, cooling, and escape of relativistic protons, electrons, and secondary electrons (and positrons) from the inner $\sim$100 pc radius of the Galaxy. This is the approximate region for which the HESS telescope has reported (Aharonian et al. 2006) a diffuse, TeV γ-ray flux. To match the TeV data we have collected archival $\sim$GHz radio continuum data covering the same region (see Appendix D of (Crocker et al. 2011b) for radio data sources) and also GeV data (Chernyakova et al. 2011). As justified elsewhere (Crocker et al. 2011b), in our modelling we assume that the particle astrophysics can be accurately described to be in quasi-steady state and that the particle transport timescale is energy-independent.

Our modelling approach is to find – as a function of environmental and other parameters – the steady-state populations of relativistic protons and electrons within the region of interest. (Note that in our modelling we neglect for simplicity the poorly-constrained ionic component of the CR hadronic population heavier than protons.) We then self-consistently determine (for the same environmental parameters) the radiative output of these populations. Radiative processes are neutral meson decay for protons and synchrotron, inverse-Compton and bremsstrahlung for electrons. We self consistently track both primary and secondary electron emission in our radiative modelling. Finally, we use a χ^2 minimization procedure to determine the parameters describing the proton and electron populations whose radiative outputs in the given ISM environment give the best fit to the $\sim$ GHz radio continuum spectrum and the ~TeV γ-ray spectrum detected from the HESS field.

4. Results of Galactic centre modelling

Our fitting procedure finds acceptable fits for magnetic field amplitudes around ~ 100 μG, wind speeds around $v_{\rm wind}$ ~ few×100 km/s, total power in all non-thermal particles of ~ 10^{39} erg/s, gas densities around n_H ~ 10 cm^{-3}, injection spectral indices γ ~ 2.4, ionization rates of ζ ~ 10^{-15} s^{-1} and electron to proton ratios (at injection at 1 TeV) of κ_{ep} ~ 10^{-2}.

On the basis of our modelling we can determine a number of interesting facts about the GC. Firstly, the totality of non-thermal signals require a contribution from both primary electrons and protons. Neither scenarios where primary electrons alone (in which the observed TeV emission is mostly provided by IC emission) nor where primary protons alone (in which secondary electrons supply the observed synchrotron radiation) provide acceptable fits to the data. This latter may be in contrast to the case presented by star-bursts where it has been claimed (Thompson et al. 2006) that secondary electrons probably do supply most of the observed synchrotron emission.

Secondly the gas environment where the non-thermal radiation is being generated is less dense than ~ 60 cm^{-3} (at 2σ confidence) with a best fit value close to 1 cm^{-3}. Given that the upper end of the allowed n_H range is less than the volumetric average gas density through the region (~ 120 cm^{-3}) this is an indication that CRs – even the > 10 TeV protons responsible for generating the TeV γ-ray emission do *not* penetrate into the densest gas in the region (where star-formation is occurring). This is, again, apparently in contrast to the situation presented by star-bursts where, it has recently been claimed (Papadopoulos 2010), CRs modify the gas conditions and chemistry where star-formation is occurring, biasing the initial mass function towards more massive stars.

This result – that GC cosmic rays do not penetrate into the dense gas – is consistent with another finding: a powerful, star-formation driven superwind blows out of the region with a speed of $\gtrsim$ 200 km/s. Given the wind, comparison of relevant timescales indicates that CRs do not remain long enough in the region to penetrate into the dense molecular gas. We note that the CRs, however, do apparently constitute important sources of heat and ionization for the warm, diffuse molecular gas phase enveloping the molecular gas cores in the GC environment.

5. Connection to the Fermi Bubbles

The wind out of the GC we have identified above carries a power of ~ 10^{39} erg/s out of the region, as we have emphasised, and this is precisely enough, in steady state and assuming the Bubbles represent thick targets to the injected protons (i.e., that the situation is one of *saturation*), to sustain the observed 1-100 GeV luminosity of the Bubbles of 4×10^{37} erg/s. This scenario explains many aspects of the Bubbles' non-thermal and thermal phenomenology:

1. The hard spectrum of the γ-rays is explained: in contrast to the situation in the Galactic disk where energy-dependent confinement implies a steepening of the in situ spectrum of CRs away from their injection distribution, the Bubble CRs, trapped independently of energy by hypothesis, follow their injection distribution.
2. Likewise the hard-spectrum 'WMAP haze' (Finkbeiner et al. 2004; Dobler & Finkbeiner 2008), coincident at lower Galactic latitudes with the γ-ray emission, is explained in this scenario as a result of *secondary* electron synchrotron emission which, again, would provide a signal of precisely the right luminosity. (We note in passing that decay of charged mesons – which leads to secondary electrons and positrons – also produces high-energy neutrinos and that the Bubbles should also be a significant source for a future, km^3, Northern Hemisphere neutrino telescope.)
3. The (Su et al. 2010) down-turn in the Bubbles' SED below ~GeV is naturally explained by π^0 decay kinematics.

The 'cost' of the above scenario is the long timescales implied: given the low-density of the Bubble plasma, $\lesssim 0.01$ cm^{-3}, the *pp* loss time blows out to $\gtrsim$ 5 Gyr and the Bubbles are required to have existed for at least this time and to effectively trap CR protons (up to at least ~TeV) over the same timescale. Thus one requires that the GC has sustained injection of $\sim 10^{39}$ erg/s in CRs into the base of the Bubbles for multi Gyr timescales.

Such might seem hard to credit but is actually not unreasonable: the morphology of the Bubbles privileges the GC and the GC is perhaps the single, spatially-localized site in the Galaxy where SF over multi-Gyr timescales is assured (Serabyn & Morris 1996) and, indeed, where luminosity function studies independently suggest that the star formation rate has been steady and continuous for multi-Gyr timescales (Figer et al. 2004). While by no means required by our scenario, it is interesting that the *current* level of GC star-formation – and resulting cosmic ray luminosity – is close to the time-averaged value required in our scenario for the origin of the Bubbles; this suggests a system in steady state (and thus an interesting point of difference between the GC and starbursts in which the gas supply is being used-up at a non-sustainable rate). Note that, quite non-trivially, the super-wind outflow from the GC can supply the *mass* ($\sim 10^8 M_\odot$) and *enthalpy* content ($\sim 10^{57}$ erg) of the Bubbles *provided* that it operates for the same multi-Gyr timescales required by the saturation/hadronic scenario.

A final couple of notes are in order. Firstly, aside from the sustained star-formation occurring in the GC, an a priori suspect to ultimately power the Bubble emission is the central, supermassive black hole (SMBH) (Su et al. 2010; Guo & Mathews 2011). In the sort of hadronic scenario we have explored this would – just as for star-formation and concomitant supernova activity – be required to generate a time-averaged power of $\sim 10^{39}$ erg/s in CRs. It is interesting in this context, then, that such a cosmic ray luminosity is rather close to the *minimum* required by analysis of the central, point-like GeV γ-ray source under the assumption that it is hadronic in nature (Chernyakova et al. 2011). Regardless of whether it is GC star-formation or low-level , sustained activity of the SMBH that energises the Bubbles, in our hadronic scenario these remarkable structures are perfect calorimetric recordings of GC activity over the history of the Milky Way.

6. Discussion

JAN TAUBER: Is the scale factor relating gamma-rays to H_2 to column density different in the GC than in the rest of the Galactic plane.
ROLAND CROCKER: Yes. In fact there is likely very little H_2 in the Bubbles – most of the 'target' mass on which the *in situ* hadronic cosmic rays collide is represented by plasma. The scale factor is, in general, quite different because the Bubbles' cosmic ray population is different (in both normalization and spectrum) to that found in the plane.

Acknowledgements. I gratefully acknowledge my collaborators: David Jones, Felix Aharonian, Casey Law, Fulvio Melia, Tomo Oka, and Jürgen Ott.

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