Connecting the asymmetry of North Polar Spur and Loop I with Fermi Bubbles

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ABSTRACT
The origin of North Polar Spur (NPS) and Loop-I has been debated over almost half a century and is still unresolved. Most of the confusion is caused by the absence of prominent counterparts of these structures in the southern Galactic hemisphere (SGH). This has also led to doubts over the claimed connection between the NPS and Fermi Bubbles (FBs). I show in this paper, that such asymmetries of NPS and Loop-I in both X-rays and γ-rays can be easily produced if the circumgalactic medium (CGM) density in the southern hemisphere is only smaller by ≈ 20% than the northern counterpart in case of a star formation driven wind scenario. The required mechanical luminosity, \( L \approx 4 \times 10^{40} \text{ erg s}^{-1} \) (reduces to ≈ 0.3 M_⊙ yr^{-1} including the non-thermal pressure) and age of the FBs, \( t_{age} \approx 28 \text{ Myr} \), are consistent with previous estimations of a star formation driven wind scenario. The main reason for the asymmetries is the projection effects from the at Solar location. Such a proposition is also consistent with the fact that the southern FB is ≈ 5° bigger than the northern one. The results, therefore, indicate a common origin of the NPS, Loop-I and FBs from the Galactic centre (GC).

Key words: Galaxy: – centre, outflow, X-ray, gamma-ray

1 INTRODUCTION
North Polar Spur is the second largest structure in the sky that extends from Galactic longitude \( l \approx 20° \) to \(-30°\) and Galactic latitude \( b \approx 10° - 70° \) in the form of an arc with a thickness of \( \sim 15° \). This is encircled by another structure called the Loop-I feature that extends \( \sim 10° \) beyond the NPS in almost all directions. Both these structures are visible in X-rays and γ-rays in northern Galactic hemisphere towards the centre of our Galaxy (Berkhuijsen et al. 1971; Sofue & Reich 1979; Snowden et al. 1997; Sofue 2000).

Although there are faint indications of southern counterparts (see Fig 13 of Ackermann et al. 2014), the absence of prominent signatures in the southern hemisphere has shadowed the truth behind the origin of these structures. Despite several claims by Sofue (1977, 1984, 1994, 2000, 2003); Bland-Hawthorn & Cohen (2003); Kataoka et al. (2013); Sarkar et al. (2015b); Sofue et al. (2016); Kataoka et al. (2018) that the NPS is ‘Galactic centre’ phenomena, the origin of the NPS still remains debated even after half a century of the first discovery of these structures. The main reason is the absence of significant counterparts in southern hemisphere and a superposition of a nearby (\( \sim 200 \text{ pc} \)) OB association, Sco-Cen along the line of sight. This has led a part of the scientific community to believe that the NPS/Loop-I are compressed shells collectively driven by several supernovae (SNe) from Sco-Cen OB association (Berkhuijsen et al. 1971; Egger & Aschenbach 1995).

There are, however, growing evidences that the NPS is not of a ‘Local origin’ and that its distance correlates well with the ‘Galactic centre origin’ scenario. X-ray observations by Kataoka et al. (2013); Lallement et al. (2016a) indicate that the NPS is highly absorbed by a hydrogen column density up to, \( N_H \sim 4 \times 10^{21} \text{ cm}^{-2} \) towards the Galactic disc indicating a distance \( \gg 200 \text{ pc} \). Although, most of the volume within 150 pc is occupied by the local bubble (Egger & Aschenbach 1995), it, in principle, possible to achieve such a high column density within \( \lesssim 200 \text{ pc} \) provided there is compressed wall of high density gas at 15 – 60 pc region between the local bubble and the NPS (Willingale et al. 2003). Although, observations by Lallement et al. (2014) indicate the presence of a high density shell towards the NPS, the required column density still falls short. This indicates the NPS to be beyond \( \sim 4 \text{ kpc} \) (see Fig 11 of Lallement et al. 2016b).

By analysing O viii Ly-α and Ly-β and other Lyman series lines from Suzaku and XMM-Newton spectrum, Gu et al. (2016) also found that the lines are well explained if they are absorbed by a 0.17 – 0.20 keV ionised medium with required hydrogen column density \( N_H \sim 5 \times 10^{19} \text{ cm}^{-2} \). This value is much more than what the local bubble could have provided (\( \sim 5 \times 10^{-3} \times 200 \text{ cm}^{-3} \) pc \( \approx 3 \times 10^{18} \text{ cm}^{-2} \)).

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Moreover, the temperature of the local bubble ($\sim 10^6$ K; Egger & Aschenbach 1995) is also less than the required value. On the other hand, such temperature and column density for the absorption is easily achievable if the NPS is $\sim 8-10$ kpc into the CGM, assuming $T_{\text{CGM}} \approx 0.2$ keV and density $\sim 10^{-3} m_p$ cm$^{-3}$ (Henley & Shelton 2010; Miller & Bregman 2013, 2015). Another factor that goes against the NPS to have a local origin is its metallicity. Fitting of X-ray spectrum shows that the metallicity of the NPS is $\sim 0.3-0.7 Z_{\odot}$ (Kataoka et al. 2013; Lallement et al. 2016a) which is close to the CGM value ($\sim 0.5 Z_{\odot}$; Miller & Bregman 2015) than that of the local interstellar medium ($\approx Z_{\odot}$; Maciel & Costa 2010).

The estimated density ($\approx 2 \times 10^{-3} m_p$ cm$^{-3}$), temperature ($\approx 0.25-0.35$ keV) and metallicity ($\approx 0.3-0.7 Z_{\odot}$) of NPS are suggestive of a structure in the Galactic CGM compressed by a Mach $\sim 1.5$ shock which could have been originated from the Galactic centre (Kataoka et al. 2013). This particular conclusion has far reaching implications towards understanding the origin of the Fermi Bubbles (FBs) as it directly constrains the energetics and thus the age of these bubbles and rules out many existing models.

Since the discovery of the FBs (Su et al. 2010) and further studies (Ackermann et al. 2014; Keshet & Gurwich 2017b,a), there have been a number of arguments regarding the origin of these bubbles. The arguments, can be classified into three main categories - (i) high luminosity ($\sim 10^{42-44}$ erg s$^{-1}$) wind driven by the central black hole (Zubovas et al. 2011; Guo et al. 2012; Zubovas & Nayakshin 2012; Yang et al. 2012; Yang & Ruszkowski 2017) requiring the age of FBs to be $\approx 2$ Myr, (ii) low luminosity ($\sim 2 \times 10^{41}$ erg s$^{-1}$) wind driven by accretion disc around the central black hole, with $t_{\text{age}} \approx 12$ Myr (Mou et al. 2014, 2015) and (iii) star formation driven wind (star formation rate $\approx 0.1-0.3 M_{\odot}$ yr$^{-1}$) with estimated age of $\approx 25-300$ Myr (Crocker et al. 2015; Sarkar et al. 2015b). There are also other constrains from O viii to O vii line ratio towards the FBs that are in favour of option ii and iii (Miller & Bregman 2016; Sarkar et al. 2017). Such a variety of arguments crucially depend on whether one considers the NPS, Loop-I and FBs to be a ‘common origin’ or not and would collapse to a small parameter space if we can answer the very origin of the NPS and Loop-I.

Despite a number of arguments regarding the NPS/Loop-I to be a Galactic centre (GC) phenomena, their origin is still questioned and revolves around the fact that these structures are asymmetric across the Galactic disc. Interestingly, Kataoka et al. (2018) speculates that such an asymmetry could have been originated from an asymmetric density in the southern hemisphere. However, the fact that both the northern and southern FBs are almost of same size lead them to conclude that the NPS and Loop-I are probably a result of previous star-burst episode of the GC. In this paper, I show that a common origin for NPS, Loop-I and FBs is possible and that the asymmetric nature of the NPS and Loop-I can be obtained by having a local asymmetry in the CGM density without affecting the symmetry of FBs.

The base of the arguments, presented in this paper, crucially depend on the projection effects of the large scale structures. It has been shown by (Sarkar et al. 2015b, hereafter SNS15) that the NPS/Loop-I are the outer shock (OS) of a star formation driven wind and has reached a distance of $\approx 8$ kpc starting $\approx 27$ Myr ago from the GC. Since we are at $\approx 8.5$ kpc away from the GC, the projection effects put this OS at $b \sim 70^\circ$ and $l \sim 60^\circ$. Now, if the CGM density in the southern hemisphere is slightly lower then the OS in that hemisphere has just run past the Solar system and, therefore, does not appear have a clear signature of a shock. The FBs, if considered to be the contact discontinuity (CD), then does not have to be very asymmetric. This would solve the tension between an asymmetric NPS/Loop-I and symmetric FBs as feared by Kataoka et al. (2018).

The rest of the paper provides full details of the above arguments and presents numerical studies in a realistic Galactic environment generating X-ray and $\gamma$-ray sky maps that can be compared with the actual observations from ROSAT and Fermi Gamma-ray Space Telescope.

2 NUMERICAL SET UP

This problem is studied by performing hydrodynamical simulations, without magnetic field and cosmic rays (CR). The simulations are performed using PLUTO-V4.0 (Mignone et al. 2007). Since the shock structure crucially depends on the exact density distribution, we pay careful attention to the initial numerical setup. This set up is exactly the same one as presented in (Sarkar et al. 2017, hereafter SNS17) (which was adapted from Sarkar et al. (2015a) to represent our Galaxy) except a few modifications.

2.1 Initial condition

In SNS17, we considered that the CGM ($T_{\text{CGM}} = 2 \times 10^6$ K) is in hydrostatic equilibrium with the background gravity of dark matter, stellar disc and bulge. The parameters for the gravity and CGM temperature was fixed to best match the observed values. The resultant density distribution of the CGM was found to mimic the inferred density distribution from the O viii and O vii line emissions. I have, however, introduced some modifications to SNS17 set up to make it suitable for the present study.

A warm ($\approx 5 \times 10^6$ K) and dense ($\sim 1 m_p$ cm$^{-3}$) gaseous disc in the initial density distribution has now been introduced. The disc gas is assumed to be rotating at 97.5% level of the rotation curve. The rest of the support against gravity is provided by the thermal pressure. I also introduce a rotation to the hot CGM to comply with the observations of Miller et al. (2016). The speed of rotation, however, is assumed to be only a fraction ($f_R = 1/3$) of the Galactic disc rotation at that cylindrical radius ($R$). Although, Miller et al. (2016) find that the CGM rotation speed is $\sim 180$ km s$^{-1}$, their assumption of a spherical gaseous distribution makes this value uncertain. A proper estimation of the CGM rotation would require self consistent consideration of the flattening of the CGM arising due to rotation. Since that is not the main focus of this paper, I consider $f_R$ to take different values (1/3, 1/2 or 2/3) to make up for this caveat. The exact pressure and hence the density distribution is then obtained by assuming that the disc gas and the CGM are both in steady state equilibrium with the background gravity (see Sarkar et al. 2015a, for details).

I also switched off radiative cooling for $|z| \leq 1$ kpc to avoid artificial radiative cooling in the disc. An active cooling
in this region would make the numerical disc to collapse into a thin layer of cold gas. In reality, turbulence generated by SN activity and infalling gas are responsible for maintaining a fluffy disc (Krumholz et al. 2017). Since the current setup does not contain any of these physics, switching off the cooling in the disc is a way around this issue. As mentioned earlier, the NPS/Loop-I or FBs are structures in the CGM, therefore, this implementation is not expected to affect the results.

To achieve the purpose of this work, I assume that the CGM density in the southern hemisphere is 20% less than the northern counterpart. Since this introduces a pressure imbalance across the galactic disc, I further set the temperature of the southern CGM 20% higher than the northern one. This temperature asymmetry is not very realistic but it does not introduce any artifacts in the sky maps as the X-ray emissivity is only weakly dependent on the temperature compared to the density. The density asymmetry in the CGM can be caused either due to the motion of our Galaxy through the local group that caused an asymmetric ram pressure on the CGM or some previous star formation wind activity. Although the motion of our Galaxy towards the centre of the local group (somewhat similar direction towards the Andromeda galaxy) is almost parallel to the Galactic disc Van Der Marel et al. (2012), a local density asymmetry till ~ 30 kpc can still be present in the CGM.

2.2 Grid and energy injection

The computational box is chosen in 2D spherical coordinates which, by definition, assumes axisymmetry. The box extends till 15 kpc in radial direction and from 0 to π in the θ-direction. A total of 1024 × 512 grid points were set uniformly in radial and θ-direction. The resolution of the box is, therefore, 15 × 6 pc² at r = 1 kpc and 15 × 61 pc² at r = 10 kpc. Both the boundaries in the r-direction were set to outflow, whereas, the θ boundaries were set to be axisymmetric (i.e. only vφ and vθ is reversed).

Supernovae energy were added within central 100 pc in the form of thermal energy. A constant mechanical luminosity was provided assuming a constant star formation rate (SFR) based on a Kroupa/Chebrier IMF and starburst99 (Leitherer et al. 1999) recipe. The mass and energy injection rate are, thereafter, given by

\[ M_{\text{inj}} = 0.1 \text{ SFR} \]

\[ L = 10^{41} \times \frac{\text{SFR}}{M_{\odot} \text{ yr}^{-1}} \text{ erg s}^{-1} \]  \hspace{1cm} (1)

where, a only a 30% of the SNe energy is assumed to survive the interstellar radiation loss in the initial SN expansion phase and become available for driving a large scale wind.

In all the simulations presented here, I assume a mechanical luminosity \( L = 4.5 \times 10^{40} \text{ erg s}^{-1} \) which was found to match the observed X-ray and γ-ray signatures of the NPS and the FBs in SNS15. If converted directly to SFR, this luminosity would imply SFR \( \approx 0.45 M_{\odot} \text{ yr}^{-1} \). We, however, should keep in mind that the non-thermal components like magnetic field and cosmic rays can contribute a large fraction of this energy and, therefore, the required star formation rate would decrease further from this value as described in SNS15.

\[ \text{This value is somewhat arbitrary and is a typical for star forming regions. This particular choice, however, does not have much influence on the size of the OS or the contact discontinuity. It, however, slightly affects the shape of FBs as can be seen in Figure A1 of Sarkar et al. (2017).} \]
Figure 2. The outer edge of the FBs taken from Su et al. (2010). The southern bubble has been inverted in latitude to compare it with the northern bubbles. There is a clear signature that the southern bubble is ≈ 5° bigger than the northern one.

3 RESULTS AND DISCUSSION

The evolution of density for \( f_6 = 1/3 \) has been shown in Figure 1. As can be seen, the structure of the outflowing gas is similar to a wind driven shock as studied by Castor et al. (1975); Weaver et al. (1977). In the inner part, it contains a free wind region which undergoes a reverse shock shortly. The wind material extends till the contact discontinuity (CD) beyond which the shocked CGM continues till the OS. Since the mass injected by the SNe driven wind is very small, the region inside the CD has low density gas which makes it suitable for hosting a X-ray cavity. Note that the γ-ray or radio emission, on the other hand, depend on the CR energy density which is dependent on the presence of shocks and turbulence. Given that there is a reverse shock (Mach \( \sim 10 \)) and a turbulent medium inside, it is likely that this region hosts high energy cosmic ray electrons and, therefore, produce the observed FBs or the microwave haze. This arguments were used by (Mertsch & Sarkar 2011, SNS15) to assume that the FBs can be represented by the inner bubble extending all the way till the CD. Due to the lack of cosmic ray physics in the current simulations, I also follow the same arguments. While this argument is persuasive and likely true, a better understanding should, in any case, be built by performing numerical simulations including both CR physics and magnetic field.

Based on the above arguments, the age of FBs is the time when the CD reaches \( \approx 50° \), i.e. \( t_{age} \approx 28 \) Myr as can be seen in the third panel of figure 1. Note that, here \( t_{age} \) is taken when the northern FB reaches \( 50° \) (observed size of the northern FB). The southern bubble, however, appears to be \( \approx 7° \) bigger in latitude. It is indeed interesting to note that although both the observed FBs are considered to be of similar size, a careful look at these bubbles reveal that the southern bubble is \( \approx 5° \) bigger than the northern one. In Figure 2, I re-plotted the outer edge of the FBs (taken from Su et al. 2010) to establish this point. The figure shows a considerably larger southern bubble in all directions except in the bottom left part which may occur due to local density variation.

3.1 X-ray sky map

As mentioned in earlier discussion, the projection effects are very important while comparing simulations with observations of large structures in our Galaxy. I have made use of the module PASS\(^2\) to produce proper projection effects at the Solar location.

Figure 3 shows 0.5 – 2.0 keV X-ray sky map generated at \( t_{age} = 28 \) Myr from simulations \(^3\) with CGM rotation of \( f_6 = 1/3 \). \(^4\) It shows the presence of features very similar to the NPS and Loop-I in the northern hemisphere along with the absence of these features in the southern part. A lower density in the southern hemisphere affects the surface brightness in two ways. Firstly, a 20% lower density means a \( \sim 40\% \) drop in X-ray brightness since the emissivity is \( \propto n^2 \).

Secondly, due to a lower density the shock runs faster in the southern part and at \( t = t_{age} \), the OS just crossed us while the northern shock is still in front of us. Once we are inside shock, the projection effects makes it hard for us to detect any such shock in the southern hemisphere.

The NPS, as seen in the current simulations, is not simply the shell that extends from the CD to the OS (in contrast to what was seen in SNS15). As can be noticed in Figure 1 that there are few shocks present inside the CD and the OS. Although, the presence if these shocks are not expected from

\(^2\) Projection Analysis Software for Simulations (PASS) described in SNS17. This code is freely available at https://github.com/kcsarkar/

\(^3\) An extended box of 200 kpc is also included to account for the emission beyond the computational box. The density asymmetry in the SGH, however, iss considered only till 50 kpc.

\(^4\) See appendix for maps with CGM rotation of \( f_6 = 1/2 \) and 2/3.
simple analytical considerations, they arise due to presence of an inhomogeneous medium and a low luminosity wind. For a typical wind scenario where the luminosity is very high, the wind is able to overcome the effect of disc pressure and thus follow a standard wind structure. However, for a low luminosity wind where the oblique ram pressure of the wind is just larger than the disc pressure, the free wind gets nudged at certain moments and thus produce a variable luminosity wind. The shocks between CD and OS are generated due to such nudging. Note that this is also a channel by which the disc material gets entrained by the free wind and can produce high velocity warm winds Sarkar et al. (2015a).

The NPS is, therefore, the projection of one such shock close to the CD and does not have to be extended till the Loop-I (See third panel of Fig 1). While such a shock follows the CD, it does not necessarily follow the outer edge of the γ-ray emission (as can be understood from Fig. 3 and 4). We speculate that such secondary shocks may also be the origin of the inner arc and outer arc. It is also possible that the shock edge detected in Keshet & Gurwich (2017a) could be one of such secondary shocks.

3.2 γ-ray sky map

To generate the γ-ray map, I follow SNS15 and assume that the main source of the γ-ray emission is via inverse Compton of cosmic microwave background by high energy CR electrons (CRe) 5 and that the total CR energy density as if assumed to be 15% of the local thermal energy density at any grid location. The CRe spectrum inside the FBs (in this case, the CD) is assumed to be \( dN/dE \propto E^{-2.2} \) (Su et al. 2010; Ackermann et al. 2014), which is also the electron spectrum required for explaining the microwave haze (Planck Collaboration et al. 2013). It is, therefore, generally believed that both the radio and γ-ray originated from the same population of CRe. Since such high energy CRe is expected to cool down via inverse Compton and synchrotron emission, a break at Lorentz factor \( \Gamma = 2 \times 10^6 \) is also assumed. After this break the CRe spectrum follows \( dN/dE \propto E^{-3.2} \).

Outside the CD and inside the OS, a softer CRe spectrum is assumed, \( dN/dE \propto E^{-2.4} \) and a break at \( \Gamma = 2 \times 10^6 \) is considered. This spectrum is consistent with the estimated value for the Loop-I (Su et al. 2010) although the break location and the cut-off frequency is somewhat uncertain. A softer spectrum is indeed expected at the OS as it is much weaker (Mach ~ 1.5) than the reverse shock inside the FBs. Note that the above prescribed assumptions to get γ-ray emission are very simplistic. A better approach requires a self-consistent implementation of the evolution of CR spectra in real time. Our focus in this section is, however, only to show the size and shape of the FBs and Loop-I.

Figure 4 shows the γ-ray sky map at 5 GeV, generated at \( t = 28 \text{ Myr} \) for CGM rotation of \( f_b = 1/3 \). It shows a good match for the size and shape of the FBs although the surface brightness inside the FBs is not as uniform as the observed ones. This can be attributed to the simple assumption of CR energy density to be a constant fraction of the thermal energy density. In reality, the CR behaves as a relativistic fluid (adiabatic index = 4/3) and, therefore, does not exactly follow the Newtonian plasma (adiabatic index = 5/3). Besides, the CR diffusion and the effect of the magnetic field in CR propagation is also not taken into account in the current numerical simulations. Diffusion can make the CR energy density more uniform than the thermal pressure, while the inclusion of magnetic field can make the outer edge of the simulated FBs much smoother than as seen in observations.

Similar to the X-rays, a larger structure beyond the FBs is also noticed. This may correspond to the Loop-I structure seen in the northern sky. The surface brightness and contrast with the background seem to match quite consistently. However, an excess emission beyond the southern FB can be noticed, although no shock structure is clearly identifiable. This excess emission is in contrast with the observations. However, we should remember that, in the southern hemisphere, we are inside the shock and, therefore, the observable CRe spectrum is not the same as the northern Loop-I, it can be steeper due to lack of further re-acceleration of CRe behind the OS. This would mean that there is less amount of excess surface brightness in the southern hemisphere. For an example, the γ-ray emissivity for a \( \propto E^{-2.45} \) CRe spectrum can be only 60% of the emissivity for a \( \propto E^{-2.4} \) spectrum, considering everything else to be the same. Therefore, it is possible that the excess brightness in the Southern part is not distinguishable from the background. At this point, it should be noted that although there is no clear signature of a southern counterpart of Loop-I is observed, two rising γ-ray horns are clearly visible in the observations by Ackermann et al. (2014) (see their figure 13).

4 CONCLUSION

In this paper, I demonstrated the feasibility of an idea that the NPS, Loop-I and FBs can have a common origin despite the asymmetry of NPS/Loop-I across Galactic disc and apparent symmetry between the FBs. I show that a density

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5 It was shown in SNS15 that a hadronic process is ineffective in producing enough surface brightness for the FBs.
asymmetry, as small as 20%, in the southern hemisphere can produce the sizes, shapes and surface brightness in X-ray and γ-ray along with the asymmetric signatures of the NPS and Loop-I strikingly similar to the observed ones. This asymmetry requires the southern FB only ≃ 7° bigger than the northern one, which is consistent with the observations that the southern bubbles is ≃ 5° bigger than the northern one. Note that this particular value of 20% is only a choice to prove the feasibility of the idea. At this point, it is not very clear how such asymmetry could have originated. Best guesses are either from the motion of our Galaxy in the local group which caused an asymmetric ram pressure to the CGM or a previous activity of asymmetric SNe-driven wind.

At this point, it is interesting to note that the same projection effects would also appear if the energy injection happens slightly below the Galactic mid-plane. In this case, the OS in southern hemisphere would be given a head start compared to the northern part. Even then, the southern shell would still be visible in X-ray as the density of the shell is same as the northern part. Besides, the observations already put the star forming region at the Galactic centre roughly at the mid-plane. Also, note that Such a projection model works only in case of a SNe driven wind and not in AGN driven winds. As can be seen in Fig 4 of SNS17 that the AGN driven bubbles are more vertical and, therefore, are not expected to respond to such a projection effects at $t = f_{age}$ as presented in this paper.

One concern is that the simulations are performed only at one mechanical luminosity $4.5 \times 10^{40}$ erg s$^{-1}$that corresponds to SFR $\approx 0.5 M_\odot$ yr$^{-1}$. This conversion, however, may change depending on the effect of non-thermal pressures, like the cosmic ray and magnetic pressure are taken into account. As seen in SNS15, the total non-thermal contribution is almost 30% of the thermal contribution. This makes the required star formation rate $\approx 0.3 M_\odot$ yr$^{-1}$for producing the above mechanical luminosity. This value is almost factor of 2 – 3 higher compared to observed value of $\approx 0.1 M_\odot$ yr$^{-1}$ (Yusef-Zadeh et al. 2009; Immer et al. 2012; Koepferl et al. 2015). A further limitation is the absence of proper CR physics and magnetic field in the simulations. This forces one to assume some prescriptions while calculating the non-thermal emission and also affects the conversion between the mechanical luminosity to SFR.

Despite these limitations, the potential of the arguments presented in this paper indicates towards a common origin of the NPS, Loop-I and the FBs.

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APPENDIX A: EFFECTS OF CGM ROTATION

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the author.

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Figure A1. Density structure for simulations with different CGM rotation ($f_h$). The contours are plotted at $t_{age} = 28$ Myr. With higher CGM rotation (higher $f_h$), the density becomes more flattened.
Figure A2. X-ray sky map at 0.5 – 2.0 keV band for different CGM rotation values. From top to bottom, $f_h = 0, 1/3, 1/2$ and 2/3. Although, an NPS like feature is not clearly visible in $f_h = 0, 2/3$ cases, the shell structure and their asymmetry can still be seen. The central bright patch is the X-ray emission due to interaction between the shock and the disc gas.

Figure A3. $\gamma$-ray sky map at 5 GeV band for different CGM rotation values. From top to bottom, $f_h = 0, 1/3, 1/2$ and 2/3. Although the sizes of the Fermi Bubbles match with the observations, the surface brightness is not uniform throughout the surface. This is probably due to absence of proper evolution of cosmic ray energy density and diffusion.