The WMAP haze from the Galactic Center region due to massive star explosions and a reduced cosmic ray scale height

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ABSTRACT

One important prediction of acceleration of particles in the supernova caused shock in the magnetic wind of exploding Wolf Rayet and Red Super Giant stars is the production of an energetic particle component with a E^{-2} spectrum, at a level of a few percent in flux at injection. After allowing for transport effects, so steepening the spectrum to

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 $E^{-7/3}$, this component of electrons produces electromagnetic radiation and readily explains the WMAP haze from the Galactic Center region in spectrum, intensity and radial profile. This requires the diffusion time scale for cosmic rays in the Galactic Center region to be much shorter than in the Solar neighborhood: the energy for cosmic ray electrons at the transition between diffusion dominance and loss dominance is shifted to considerably higher particle energy. We predict that more precise observations will find a radio spectrum of $\nu^{-2/3}$, at higher frequencies ν^{-1} , and at yet higher frequencies finally $\nu^{-3/2}$.

Subject headings: supernovae: general — cosmic rays — acceleration of particles — stars: winds, outflows — shock waves — radio continuum: general

1. Introduction

Scanning all sky the WMAP satellite discovered a haze in the region of the Galactic center, with radio frequencies up to near 100 GHz, and a relatively flat spectrum (Finkbeiner 2004a, 2004b; Hooper et al. 2007; Dobler & Finkbeiner 2008; Caceres 2009). There are a number of possible explanations for this haze, as discussed in these papers, such as annihilation of dark matter, and also attributing the haze to various stars (Bandyopadhyay et al. 2009); however, those authors conclude their specific proposal fails. The radio spectrum of this haze is very much flatter at such frequencies than predicted on the basis of cosmic ray electron data (Wiebel-Sooth & Biermann 1999), and so there is an apparent conflict. Here we estimate whether this extra emission can be attributed to the polar cap component of cosmic rays, emanating from massive star explosions, following reasoning in earlier work (Biermann 1993, Biermann & Cassinelli 1993, Stanev et al. 2009), finally definitively showing the existence of the cosmic ray polar cap component. In the following we use cgs units.

We find, that the polar cap component can explain the data. It requires the magnetic turbulence in the Galactic center region to be much stronger than in the Solar neighborhood (see Aharonian et al. 2006, Becker et al. 2009), so that first the diffusion scale height for cosmic rays is reduced, and so second the transition between the diffusion-dominated regime and the loss-dominated regime is shifted to much higher energy than in the Solar neighborhood.

2. Cosmic ray transport and loss across the Galaxy

Cosmic rays are injected from massive star explosions, with predicted spectra of $E^{-2.42\pm0.04}$ from ISM-SNe (Biermann & Strom 1993), $E^{-7/3-0.02\pm0.02}$ from wind-SNe (Biermann 1993, Biermann & Cassinelli 1993), with a polar cap component at a few percent level and a spectrum of E^{-2} (Stanev et al. 1993). All these spectra are steepened by diffusive losses by 1/3, so become $E^{-2.75\pm0.04}$, $E^{-8/3-0.02\pm0.02}$, and $E^{-7/3}$ (Stanev et al. 1993). The polar cap component is limited by spatial constraints to a maximum energy of order PeV (for Hydrogen). The polar cap component is slower in its acceleration, and so has more time to interact and produce secondaries (Jokipii 1987, Meli & Biermann 2006), so naturally explaining quantitatively the ATIC, H.E.S.S., Pamela, and Fermi results for cosmic ray electrons and positrons (Pamela: Adriani et al. 2009; H.E.S.S.: Aharonian et al. 2008; ATIC: Chang et al. 2008) with such a concept (Biermann et al. 2009). H.E.S.S. (Aharonian et al., 2009) and Fermi (Abdo et al., 2009) gave further quantitative confirmation of the predictions.

In the Solar neighborhood we have a competition between diffusive losses, running with $E^{-1/3}$, and synchrotron and inverse Compton losses, running with E^{-1} . The transition for cosmic ray electrons is at about 20 GeV, so a Lorentz factor of about $\gamma_e = 10^{4.6}$. At a similar energy the wind-SN-electrons may begin to dominate over the ISM-SN-electrons, so shifting the spectrum from $E^{-2.75}$ to $E^{-8/3}$; this is visible in data comparing radio spectra with cosmic electron spectra (Wiebel-Sooth & Biermann 1999). Above this energy the spectrum is $E^{-10/3}$, before the polar cap component rises up to dominate at E^{-3} , at a transition energy of about 40 GeV, corresponding to a Lorentz factor of $\gamma_e = 10^{4.9}$. Since at that energy the ISM-SN-cosmic rays still contribute appreciable partial flux, the straight transition to polar cap dominance for wind-SN-cosmic ray particles only may be at slightly lower energy even, such as at $\gamma_e \simeq 10^{4.4}$, or even less. We note in passing, that at these energies the positrons do not contribute a strong partial flux (see the graphs in Biermann et al. 2009).

The transition between the cosmic ray spectrum contributed from most of 4π of the sphere of a shock caused by a massive star explosion, and racing through the wind, is just a function of stellar physics (Langer & Heger 1999; Heger et al. 2003); the ratio between ISM-SNe, so slightly lower mass stars, and wind-SNe, is a function of star formation activity; in a starburst, temporarily more massive stars are born (e.g. Biermann & Fricke 1977, Kronberg et al. 1985), and so their contribution to cosmic ray fluxes, including the polar cap component, is temporarily stronger relative to that of the ISM-SNe. In the Galactic Center region we may have a top-heavy mass distribution of stars, so more very massive stars (Bartko et al. 2009).

However, the transition between the diffusion regime and the loss regime, very strongly depends on the magnetic turbulence: The stronger the turbulence, the faster cosmic ray transport, and the higher the transition energy between the two regimes (Aharonian et al. 2006; Becker et al. 2009). In the Galactic Center region star formation peaks for the entire Galaxy, and so it is altogether very plausible, that the transport by diffusive leakage is much faster than in the Solar neighborhood; in fact it can be analytically shown, that the scale height for the diffusive regime scales inversely with the strength of the magnetic turbulence (Becker et al. 2009). It follows that the diffusive time scale, estimated for the Solar neighborhood at near 10^7 years, is very much shorter in the Galactic Center region.

The WMAP haze has been observed at radio frequencies between 20 and near 100 GHz, and

at about 10 μ Gauß magnetic field strength (Berkhuijsen 1994, in Beck et al. 1994; Ferrière 2009) this implies a range of cosmic ray electron Lorentz factors of γ_e from 10^{4.35} to 10^{4.7}. The precise spectrum is very difficult to determine due to the background subtraction errors; the data suggest a hardening by 0.3 in radio spectral index with respect to the normal radio emission with spectral index -0.88 (corresponding to the observed cosmic ray proton spectrum, consistent with the inferred cosmic ray electron spectrum below about 10 GeV (Wiebel-Sooth & Biermann 1999; Hooper et al. 2007); this entails that the haze spectrum is somewhere near $\nu^{-0.58}$, but with relatively large error bars. The data suggest that the flat component extends to about 100 GHZ. This then implies that the diffusive transport time scale in the Galactic Center region is at least 5 times shorter than in the Solar neighborhood (for GeV particles).

To explain the WMAP haze all we require is, a) that at these cosmic ray electron energies we are still in the diffusive regime of cosmic ray transport, and b) the polar cap component has already started to come up. This suggests a cosmic ray electron spectrum in the relevant energy range of of $E^{-7/3}$, and so correspondingly a radio spectrum at high frequencies of $\nu^{-2/3}$. Following the reasoning in Biermann et al. (2009) we can then predict the transition to the loss dominated regime, giving a radio spectrum at higher frequencies of ν^{-1} , and finally the spectrum resulting from a limited spatial reach, $\nu^{-3/2}$. The Planck satellite may be able to test these clear predictions. Due to a very strong dependence on the diffusion scale height, it is difficult to pinpoint the exact radio frequencies of the transitions between the different regimes.

2.1. Cutoff frequencies

Can we predict the frequencies of the various transitions between the three spectral regimes? The loss time of cosmic ray electrons is

$$\tau_{syn} = \frac{6\pi m_e c}{\sigma_T \gamma_e B^2 \epsilon_{IC}} \tag{1}$$

where σ_T is the Thompson cross section, γ_e is the Lorentz factor of the emitting electrons (or positrons), $B^2/8\pi$ is the magnetic field energy density, while ϵ_{IC} is the enhancement of the losses due to inverse Compton interaction with the ambient photon field.

The diffusive loss time of cosmic ray electrons is

$$\tau_{diff} = \tau_0 \gamma_{e,3.3}^{-1/3} \tag{2}$$

where $\tau_0 \simeq 10^7$ yrs, and $\gamma_{e,3.3}$ is the electron Lorentz factor at the energy corresponding to the proton rest mass, where we can estimate the time scale from cosmic ray data in the Solar neighborhood.

For a given cosmic ray electron energy the scaling of the time scale for diffusion is

$$\tau_0 \sim H_{CR}^2 B b \tag{3}$$

where H_{CR} is the diffusion scale height, about 1 - 2 kpc in the Solar neighborhood; *B* is again the magnetic field strength, and *b* is the ratio between the turbulent energy in magnetic field fluctuations, and the overall magnetic field energy density.

The transition between losses via synchrotron and Inverse Compton losses on one side, and diffusive losses on the other is at about 10 - 20 GeV in the Solar neighborhood, and at a much higher energy in the Galactic Center region, we claim.

Inserting numbers gives

$$\tau_{syn} = 10^{7.7} \text{ yrs } B_{-5}^{-2} \gamma_{e,3.3}^{-1}$$
(4)

using 10^{-5} Gauss as scale for the magnetic field.

The transition energy $\gamma_{e,3.3,\star}$ is then given by

$$\gamma_{e,3.3,\star}^2 = 10^{2.1} B_{-5}^{-6} \left(\frac{H_{CR,GC}}{H_{CR,sol}}\right)^{-6} \left(\frac{B_{GC}}{B_{sol}}\right)^{-3} \left(\frac{b_{GC}}{b_{sol}}\right)^{-3} \left(\frac{\epsilon_{IC,GC}}{\epsilon_{IC,sol}}\right)^{-3} \tag{5}$$

which we can insert into the expression for the cut-off frequency.

Using 10 μ Gauß for the magnetic field at the Galactic Center, as well as a factor of 2 between the magnetic field there and in the Solar neighborhood, and allowing a frequency of 100 GHz or higher for the haze then requires

$$\left(\frac{H_{CR,GC}}{H_{CR,sol}}\right) < 0.5 \left(\frac{b_{GC}}{b_{sol}}\right)^{-1/2} \left(\frac{\epsilon_{IC,GC}}{\epsilon_{IC,sol}}\right)^{-1/2} \tag{6}$$

Of course, this could be much less than the limit. The two factors on the right hand side, the enhancement in magnetic turbulence at the Galactic Center relative to the Solar neighborhood, and the enhancement in radiation fields, are both expected to be much larger than unity. Therefore the scale height has to be much smaller in the Galactic Center region.

However, this also illustrates, that the dependence on the precise parameters is so strong, that we may well have to determine the cutoff frequencies from observations, and from that constrain the main parameters, with the diffusive scale-height H_{CR} the most critical. Decreasing the scale height by a relatively small factor can increase the critical turnoff frequency enormously.

2.2. Flux

The observed spectrum of energetic electrons from the polar cap component is

$$\frac{dN_e}{d\gamma_e} = 10^{+4.75} \gamma_e^{-3} \text{cm}^{-2} \text{sr}^{-1} \text{s}^{-1}$$
(7)

Going down from the loss limit (Kardashev 1962) to the transition energy for the diffusion limit gives

$$\frac{dN_e}{d\gamma_e} = 10^{+1.75} \gamma_e^{-7/3} \text{cm}^{-2} \text{sr}^{-1} \text{s}^{-1}$$
(8)

This implies a density of particles of

$$C_e = 10^{-7.65} \gamma_e^{-7/3} \text{cm}^{-3} \tag{9}$$

This has been inferred for the Solar neighborhood; in the Galactic Center region the flux is likely to be higher by about the magnetic field energy density, so by about 4 (Berkhuijsen, in Beck et al. 1996). So we finally obtain an estimate of the polar cap component electrons in the Galactic Center region of

$$C_e = 10^{-7.05} \gamma_e^{-7/3} \text{cm}^{-3} \tag{10}$$

Taking a reference volume corresponding to $\theta_{\star} = 0.1$ rad, so about 6 degrees, the observations (e.g. Hooper et al. 2007) give about 4 kJy sr⁻¹ emission. Here we take just one point on their curves, and estimate the flux density from their figures, at that angular distance, and discuss the radial variation separately. This has to be matched with

$$S_{haze} = \frac{Vol}{4\pi D_{GC}^2} \, 3 \cdot 10^{-18} \, C_e \, B^{5/3} \, \nu^{-2/3} \frac{1}{\Delta\Omega} \tag{11}$$

where $\Delta \omega$ is the solid angle of this emission, as seen from us, and using $C_e \gamma_e^{-7/3}$ as the energetic electron spectrum. As $Vol \sim \theta_{\star}^3$ and $\Delta \Omega \sim \theta_{\star}^2$, the dependence of $S_{haze} \sim \theta_{\star}$, so linear. The volume of this limited region near the Galactic Center as delineated above is about $10^{64.8}$ cm³, and the distance is about 7.5 kpc, so that $4\pi D_{GC}^2 \simeq 10^{45.9}$ cm². Here we then obtain at about 100 GHz, over $\Delta \Omega \simeq 10^{-2}$ sr

$$S_{haze} = 10^{+3.55} \,\mathrm{Jy \, sr^{-1}} \tag{12}$$

to compare with $10^{3.6}$ Jy sr⁻¹, so a reasonable match, considering the uncertainties clear from the derivation.

2.3. Radial profile

Hooper et al. (2007) give an approximate flux density profile of about $s^{-1.4}$, with s being the perpendicular distance to the center of the disk. Therefore, there is an important question: How far out above the Galactic plane can we predict the flat component to be visible? Writing the losses of a charged particles moving along with the Galactic wind (Westmeier et al. 2005, Breitschwerdt 2008, Everett et al. 2008), referring the time of transition from the diffusive regime to the convective regime

$$\frac{d\gamma_e}{dt} = -\frac{1}{2}\frac{\gamma_e}{t} - \frac{\gamma_e^2}{\tau_{syn,0}}\left(\frac{t_0}{t}\right)^2.$$
(13)

Here we have used magnetic moment conservation, the asymptotic Parker regime of the wind, where the magnetic field runs as 1/r (Parker 1958), and assume a conical cut from a spherical configuration. For more cylindrical or more fountain-like geometries the factors 1/2 and $1/t^2$ get modified. We assume, that the wind is quasi stationary, and so that time t is equivalent to distance, using here polar coordinates.

There are two extreme solution: as long as the first term dominates the solution is

$$\gamma_e \sim \left(\frac{t}{\tau_0}\right)^{-1/2}.$$
 (14)

If the second term were to dominate, this condition implies

$$\gamma_e \gtrsim \frac{1}{2} \frac{\tau_{syn,0}}{t_0} \frac{t}{t_0} \tag{15}$$

so the transition energy increases with time; setting our attention at the cutoff edge at the start of the wind, where losses just begin to become important, this expression shows, that adiabatic losses always win, as the transition energy to synchrotron and Inverse Compton losses goes up with time, as we follow the particle population out along with the wind. Therefore the emission from the flatter component of the electron population stays always dominant, as the particles move out through the wind.

The derivation above also implies, that the momentum of a particle runs as $p \sim r^{-1/2}$, a spectrum $N_{CR}(p)dp$ decreases as $r^{-2/3}$, and so the emission integrated along the line of sight through the cone runs as $r^{-4/3}$, close to what is observed. Therefore this simple model lets us understand vertical profile, and spectrum.

Last we estimate how many cosmic ray electrons participate in producing the WMAP haze: We take the density from above in the nonthermal spectrum, integrate from the minimum energy of cosmic ray electrons (see Biermann et al. 2009), a solid angle of 10^{-2} sr consistent with the earlier crude numbers, the distance to the Galactic Center of about 8 kpc, and the flow velocity of about 1000 km/s, a small multiple of the escape speed. We assume, that the area around the Galactic Center participating in the flow is reasonably well described by the same length scale as what we observe on the sky, and so arrive at a crude estimate of 10^{41} s⁻¹ of polar cap cosmic ray electrons produced. The normal steeper spectrum cosmic ray electrons are a factor of order 30 (the inverse of a few percent) larger, estimated over the same area of the Galactic disk around the Galactic Center, so about $10^{42.5}$ s⁻¹, and correspondingly larger for a larger surface area, like the 3 kpc ring region, where most of the star formation happens in the Galaxy; for such a larger region the production rate is then would be another factor of about $10^{1.6}$ larger, so about $10^{44.1}$ s⁻¹. As the production of secondaries rises towards lower energy, the cosmic ray positron production may approach $10^{43.5}$ s^{-1} . The ensuing annihilation rate may explain the 511 keV emission line in the Galactic Center (e.g. Weidenspointner, et al. 2008). Obviously, this energy supply in these cosmic ray electrons is only a small fraction of the entire cosmic ray energy output even in the inner Galaxy. We will consider secondary production and the 511 keV emission line elsewhere in detail.

3. Conclusions

Following earlier reasoning we propose that massive star explosions give rise to a cosmic ray component from their polar cap, which has a flatter spectrum, but also slower acceleration times, and can so explain the WMAP haze, a zone of flatter radio spectrum at high frequencies around the Galactic Center. The condition is that in the Galactic Center region the transport of cosmic ray particles is considerably faster, so that the transition between diffusive losses and synchrotron/inverse Compton losses is shifted to higher particle energy relative to the Solar neighborhood. It can be shown (Becker et al. 2009) that the high star formation rate per area in that region of the Galaxy leads to a short transport time.

This is now further support for the concept of a polar cap component in cosmic rays from very massive star explosions (Biermann 1993, Stanev et al. 1993, Biermann et al. 2009). This also adds support for the magneto-rotational mechanism for massive star explosions (Kardashev 1964, Bisnovatyi-Kogan 1970, Ardeljan et al. 2000, Moiseenko et al. 2003), since our argument requires that the particle energy at which this component becomes relevant is very nearly the same for all very massive stars (Biermann 1993).

We argue, that in the centers of galaxies and starburst galaxies the cosmic ray diffusion loss time scales can become considerably shorter than in the Solar neighborhood. This will help understand starburst galaxies such as M82 (Kronberg et al. 1985). So we predict, that in the central parts of other galaxies as well as star burst galaxies the scale height is also considerably reduced compared to the Solar neighborhood.

Our main prediction is the spectrum of the haze as a sequence of spectral components of $\nu^{-2/3}$, ν^{-1} , and $\nu^{-3/2}$.

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