Cosmic Rays in the Galactic Center Region

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Abstract. EGRET data on the Gamma ray emission from the inner Galaxy have shown a rather flat spectrum. This spectrum extends to about 50 GeV in photon energy. It is usually assumed that these gamma-rays arise from the interactions of cosmic ray nuclei with ambient matter. Cosmic Ray particles have been observed up to \(3\times10^{20}\) eV, with many arguments suggesting, that up to about \(3\times10^{18}\) eV they are of Galactic origin. Cosmic ray particles get injected by their sources, presumably supernova explosions. Their injected spectrum is steepened by diffusive losses from the Galaxy to yield the observed spectrum. As cosmic ray particles roam around in the Galactic disk, and finally depart, they encounter molecular clouds and through p-p collisions produce gamma rays from pion decay. The flux and spectrum of these gamma rays is then a clear signature of cosmic rays throughout the Galaxy. Star formation activity peaks in the central region of the Galaxy, around the Galactic Center, the focus of this meeting. Looking then at the gamma ray spectrum of the central region of our Galaxy yields clues as to where the cosmic ray particles interact, and with what spectrum. Using the FLUKA Monte-Carlo, we have modelled this spectrum, and find a best fit for a powerlaw spectrum of cosmic rays with a spectrum of 2.34, rather close to the suggested injection spectrum for supernovae which explode into their own winds. This suggests that most cosmic ray interaction happens near the sources of injection; it has already been shown elsewhere that this is consistent with the spectrum of cosmic ray nuclei derived from spallation. One important consequence is that cosmic ray heating and ionization should be strong in the Galactic Center region.

1. Introduction

The spectrum of Galactic cosmic ray particles extends to probably \(3\times10^{18}\) eV; the various contributions have been reviewed extensively by Wiebel-Sooth & Biermann (1998), and the basic fits to the data for the various chemical elements have also been given in Wiebel-Sooth, Biermann & Meyer (1998). These cosmic ray particles interact with interstellar matter, and so spallate to produce the
secondary nuclei (see, e.g., Garcia-Munoz et al. 1987), as well as the gamma ray emission above GeV photon energy (see, e.g., Stecker 1971).

There is a new AGASA paper (Hayashida et al. 1998) suggesting that neutrons near $10^{18}$ eV are seen coming from both the Galactic Center region as well as the Cygnus region, detected by a correlation in arrival direction. The data suggest neutrons, because protons at such an energy cannot get through the Galaxy on a straight line path with its magnetic field, since at that energy the Larmor radius is about 1 kpc. The data cannot also easily be explained as gamma ray photons, since then the correlation would be stronger at lower energy even, where nothing is seen. Of course, neutrons are produced by isospin flip in p-p collisions. It is worth remembering, that the Galactic Center region, as well as the Cygnus region are the prime candidate regions for star formation and supernova activity in the Galaxy, as clearly shown in radio, far-infrared and gamma ray data. Neutrons also can get here within their life time from the Galactic Center, but not at much lower energy. This leaves neutrons as the most probable origin of these events. If this result is accepted with the interpretation as neutrons, then it strongly supports the argument that cosmic rays are indeed Galactic up to $10^{18}$ eV. However, it is also immediately obvious, that the flux of cosmic ray particles required in the source regions to produce so many neutrons as suggested by the AGASA data, needs to be rather high relative to the flux observed at Earth. This then leads to considerable ionization and heating by low energy cosmic rays in the Galactic Center region.

In this paper we wish to review first the interpretations of the cosmic ray particles in the Galactic Center region, and then show that a simple concept may be sufficient to explain the new data from EGRET, which show a rather flat gamma ray spectrum. This is a severe test for any theory of cosmic ray origin.

2. Origin of high energy cosmic rays

Our Galactic Center harbors a black hole, which probably went through many activity episodes during its growth. Therefore we want to ask first whether this activity could possibly explain high energy cosmic rays, and as a consequence gamma rays.

Biermann & Strittmatter (1987) have shown that radio galaxy hot spots can accelerate protons to about $10^{21}$ eV. Scaling this result with the power of the underlying source and using the jet/disk-symbiosis picture developed by Falcke et al. (1995 and later papers) we obtain for the maximum proton energy

$$E_{p,max} = 6.7 \times 10^{20} Q_{jet,46}^{1/2} \text{eV}$$

(1)

where $Q_{jet,46}$ is the power of the jet in units of $10^{46}$ erg/s. The most extreme inferred jet luminosity is about $3 \times 10^{47}$ erg/s, and so energies up to

$$E_{p,max} = 4.1 \times 10^{21} \text{eV}$$

(2)

appear possible (Biermann 1998a). Therefore radio galaxies and their various counterparts such as compact radio quasars (see also Farrar & Biermann 1998) are clearly a suitable source for high energy cosmic rays. The jet-disk symbiosis
does seem to work down to stellar size black holes (Falcke & Biermann 1998), and so we may be permitted to use it for intermediate powers of a proposed source.

The jet power of our Galactic Center, assuming that the compact radio source does signify the existence of a jet, is

\[ Q_{\text{jet}} = 5 \times 10^{38} \text{ erg/s} \]  

and so \( E_{p,\text{max}} = 1.5 \times 10^{17} \text{ eV} \). Therefore the activity of our central black hole is insufficient to produce neutrons at \( 10^{18} \text{ eV} \), and so is unlikely to help to explain the correlations in arrival directions in the data.

The Galactic Center region does harbor many interesting binary systems, some of which are referred to as mini-quasars; however, there again, their power is just not sufficient to explain particles near \( 10^{18} \text{ eV} \).

There is a new hot disk model, where weakly relativistic protons produce various secondaries in their interaction in the disk (Mahadevan 1998), but this model also cannot explain any particles at \( 10^{18} \text{ eV} \).

Therefore we propose to explore in the following the activity and cosmic ray injection properties of supernovae focussing on those supernovae that explode into their own stellar winds (Biermann 1997).

3. Galactic Cosmic Rays

In a series of papers Biermann et al. (1993 and later) have proposed that cosmic rays get injected from three sites predominantly:

- Supernovae that explode into the interstellar medium.
- Supernovae that explode into their own stellar wind.
- Radio galaxies and compact radio quasars.

The predictions of these models have been given in various reviews, and we summarize here briefly:

The cosmic ray particles which interact the most derive from the wind-supernovae. This happens since massive stars explode close to their birthplace, where the original material is still around from which they formed (Biermann & Tinsley 1974). Their source spectrum has been predicted to be \( E^{-2.33 \pm 0.02} \) below the knee at \( 5 \times 10^{15} \text{ eV} \) particle energy. For particles above the knee the corresponding prediction is \( E^{-2.74 \pm 0.07} \). This peculiar way of writing the expected theoretical error range signifies an asymmetric error distribution, extending here from the most probable value of 2.33 to 2.37 in the first case. The bend (to explain the knee) has been predicted to be at \( 600 Z \text{ TeV} \), where \( Z \) is the charge of the chemical element nucleus under consideration, and the cutoff is near \( 100 Z \text{ PeV} \). Because the energy of the bend depends on the charge, the element abundance gets heavier at the knee, as noted already by Peters (1959, 1961).

To understand the concept of wind-supernovae we must remember that massive stars come in a variety of clothes, which are their different wind shells:
First, stars above 8 solar masses, but below about 15 solar masses explode as supernovae, but do so directly into the interstellar medium. This is the classical case. Then stars above 15 but below about 25 solar masses explode into their wind, and that wind may be powerful enough to sweep up interstellar material into a shell mixed with shocked wind material, but the shell is still rather thin. The material in this shell is enriched in Helium from the nuclear reactions inside the star. Finally, above about 25 solar masses the winds get very powerful, leading to Wolf-Rayet stars, and is heavily enriched. In this case the wind-shell may be rather thick.

The transport through the Galaxy is described by a diffusion coefficient, which depends on the wavefield that derives from a Kolmogorov spectrum of interstellar turbulence, and so the cosmic ray spectrum is steepened by 1/3 (see, e.g., Biermann 1995), to yield $E^{-2.67 \pm 0.02}$ below the knee. This result can be directly compared with the data for Helium through Iron, which give a best fit of $E^{-2.64 \pm 0.04}$ (Wiebel-Sooth, Biermann & Meyer 1998).

However, where the interaction really happens is not clear. There are many possible points of view on this question, but two conceptually simple notions are documented in the literature:

First, there is the CR-standard model (see, e.g., Garcia-Munoz et al., 1987) that the average cosmic rays interact with the interstellar matter. In such a picture the gamma rays should have a spectrum that nicely fits the average cosmic ray spectrum, near $E^{-2.7}$. In such a picture the secondary to primary ratio of spallation products such as boron derived from carbon spallation gives the spectrum of interstellar irregularities with an implied energy dependence of the leakage time scale as $E^{-0.6}$. One problem with this argument is that there is little evidence for such a spectrum of irregularities (Biermann 1995), but it does give a good fit.

Second, there is the notion that most cosmic ray interaction happens near the source (Biermann 1998b). In such a picture the spallation leading to secondary nuclei production happens in the shell around the stellar wind, when the supernova induced shock smashes through that shell. This leads to an energy dependence for the local leakage time scale of $E^{-0.55}$ (Biermann 1998b); however, this happens only when the shell is thick enough to allow diffusive interaction to be dominant over convective losses. This latter process is likely to dominate for the more abundant, but thinner shells around slightly lower mass stars. Therefore, in such a picture we expect that the more common stars in the range 15 to 25 solar masses would produce most gamma rays. And as a corollary we expect that the gamma rays should correspond to the injection spectrum.

3.1. The failure of the CR-standard model

The standard model has been explored in two papers recently, using the best EGRET data (Hunter et al. 1997, Mori 1997). The standard model fails by a wide margin.

The failure is due to the spectrum. The observed gamma ray spectrum is just too flat in order to be produced by a cosmic ray spectrum near $E^{-2.7}$.

There are several ways out of this conundrum.
First, one might argue that the Monte-Carlo codes used to predict the gamma rays are not good enough. This is what Mori (1997) has tried. The uncertainties in the Monte-Carlos are not sufficient to explain the flat spectrum.

Second, one might argue, that pion decay does not explain the data. This has been tried by Pohl & Esposito (1998). They suggest that the spectrum can be partially derived from inverse Compton scattering off a population of energetic electrons produced by supernova remnants. In the progressive leakage of the electrons as a function of energy and time from injection the observed spectrum can be matched. If the new AGASA data are correctly interpreted with arising from energetic neutrons, then cosmic ray nucleon interaction is about as high as can possibly be, and so it is difficult to see how to avoid gamma ray production from pion decay being a strong contributor.

Conversely, a success of an alternative model that also explains other data would be very helpful, and this is what we have tried.

3.2. A fit to the data

Therefore we have adopted a simple powerlaw model for the Bremsstrahlung and inverse Compton contribution and then fitted the data with one main parameters in mind: The power law spectrum of the cosmic rays; this law is given as a strict power law in momentum from many MeV to many GeV and beyond in energy.

We have tried three different Monte-Carlo codes from CERN and Fermi-Lab to do this analysis, and we have adopted for this work the code FLUKA (specifically the version GEANT3.21/FLUKA from the CERN library). This code could readily be adapted to include the subtle effects of Helium for instance.
Fig. 1 gives the \( \chi^2_{\text{red}} \) fit as a function of spectral index. The wiggle at spectral index 2.36 is due to a systematic pattern in the data from the primary data analysis. In the plot shown here a clear minimum is visible at spectral index 2.34. This minimum is at a level of \( \chi^2_{\text{red}} \) of 1.9. Taking into account the uncertainties of the IC and Bremsstrahlung contribution this is quite acceptable. Fig. 2 gives the resulting fit, which still shows some model dependent waves from the finite resolution of the Monte-Carlo used.

The next step will be to check how high in energy we can push this model of cosmic ray interaction near the source; there are severe limits now on the inner Galaxy from the CASA-MIA experiment (Ong 1998).

4. Consequences

First of all, what the agreeable fit demonstrates is that there is a spectrum for the cosmic rays that fits their gamma ray emission. This spectrum is consistent with a power law, and is in fact quite close to the original prediction of a source spectrum for wind-supernovae.

Second, it shows that source related interaction may be worth pursuing in detail. What has not yet been done here, is a fit to the detailed isotope abundances (see the recent discussion of this point by Westphal et al. 1998). Together with the paper presented at the Hirschegg conference (Biermann 1998b) this means that there is a viable proposal how to explain a) the cosmic ray spectrum itself, b) the gamma ray spectrum, and c) the spectrum of spallation secondaries.
If this scenario could be confirmed there are some consequences also for the stars with strong winds:

- Wolf-Rayet and OB stars have shock waves running through their winds.
- These shocks accelerate electrons and produce observed radio emission (Biermann & Cassinelli 1993).
- These shocks accelerate also protons, resulting in a steep pion decay spectrum; this spectrum is steep because the Alfvénic Machnumber of these shocks is low.
- These shocks also accelerate nuclei, which can give rise in collisions to spallation products in an excited nuclear state, then explaining gamma ray lines (Nath & Biermann 1994b) from active regions of star formation.

Finally, to summarize the essential idea again, there are consequences of this scenario as well for exploding stars with strong winds:

- The supernova shock races through the wind.
- The shock accelerates particles.
- Cosmic ray injection of elements such as helium and most heavier elements originates from this acceleration.
- Once outside their site of origin the protons (and other nuclei) at energies below about 50 MeV use up their ionization and heating power near their origin (Nath & Biermann 1994a).
- In the Galactic Center region the cosmic ray induced ionization and heating should be high.

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