An annihilation fountain at the Galactic center?

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Abstract
Recently, data of taken with the OSSE experiment have been combined with scanning observations by TGRS and SMM to produce maps of the narrow Galactic 511 keV line emission (Purcell et al. 1997). A modelling of the combined data give evidence for three distinct features: the Galactic plane, a central bulge, and an extended emission region at positive latitudes above the Galactic center. It has been proposed that the high-latitude feature is associated with a fountain of radioactive debris produced by enhanced supernova activity in the Galactic center region (Dermer and Skibo 1997).

Here we discuss this scenario in more detail: we have build a 2-dimensional code to follow the development of a hydrodynamical fountain in the Galactic center region. We have then calculated the transport, cooling, and annihilation of positrons as test particles in the outflow. As a result we find difficulties with the fountain model if the positrons are produced by supernovae in a starburst near the Galactic center. Annihilation on dust grains may increase the 511 keV line flux at high latitudes. Alternatively the observed positrons may not be entirely produced by supernovae.

The model
The basic code is similar to earlier attempts to model activity in starbursts galaxies (Tomisaka and Ikeuchi 1986, 1988). It is two-dimensional and it assumes azimuthal symmetry. The cooling function is based on the work of Dalgarno and McCray (1972) and Raymond, Cox and Smith (1976). For the gravitational potential we use the model of Miyamoto and Nagai (1975), but here with readjusted parameters (Paczyński 1990).

Direct energy and matter input from supernova explosions is described preserving the stochastical nature of these events. Each supernova is assumed to add $10^{51}$ ergs of heat and $10 M_\odot$ of gas to the interstellar medium. The number of explosions per time step is determined by a Poissonian random number generator. For the general supernova heating, not the starburst, the location of each supernova is determined by random number generators for a $r^{-1/2}$ distribution within the Galactic disk and a normal distribution of dispersion 60 pc in vertical direction. The hydrodynamical equations are solved with a staggered leapfrog scheme. Positron are considered to be a by-product of the explosive event in the sense that a certain spectrum is injected instantaneously and the particles convect with the gas flow, cool and eventually annihilate. The positrons will thus be treated as test particles.
At higher energies the main energy loss processes are inverse Compton scattering, synchrotron emission, bremsstrahlung, and adiabatic cooling. At lower energies the evolution depends on the ionization state of the background medium. For simplicity we consider gas at temperatures \( T \geq 10^4 \) K fully ionized, below 5000 K the gas is assumed neutral, and in the intermediate regime 10 % ionized. In the former case cooling occurs by Coulomb interactions. If the background medium is neutral, the positrons loose energy by ionising and exciting atoms. A comprehensive summary of the relevant positron annihilation processes is given by Guessoum, Skibo and Ramaty (1997).

The cooling of the non-relativistic positrons occurs on time scales of years or less, much shorter than the hydrodynamical time scales. Therefore we treat the evolution of the positron spectrum semi-analytically (Drachman 1983). Having determined the total energy loss rate \( A(E) \) and the catastrophic loss rate \( B(E) \), we find that within a time period \( \delta t \) (e.g. the timestep of the hydrodynamical calculation) positrons at an initial energy \( E_i \) have cooled to the energy \( E_f \), where

\[
\delta t = \int_{E_i}^{E_f} \frac{dE'}{A(E')}
\]

(1)

The initial positron spectrum \( N_{\text{pos}}(E_i) \) has evolved into

\[
N_{\text{pos}}(E_f) = N_{\text{pos}}(E_i) \exp \left( \int_{E_i}^{E_f} dE' \frac{B(E')}{A(E')} \right)
\]

(2)

Since the positrons are test particles in the hydrodynamical flow, their spatial propagation can be simply described by the number conservation equation using the grand scale velocity field.

**Results**

We have investigated three basic scenarios: example 1 considers a moderate general supernova rate of 2 per Millenium with 1 kpc of the Galactic center. For a short time of half a million years a starburst occurs at a supernova rate of 20 per Millenium within 500 pc of the Galactic center. The starburst is centered 60 pc above the midplane, which in this case is sufficient to establish a one-sided outflow. The low general supernova rate causes a rather thin gas disk with little material in the halo. The strong starburst then causes rapid acceleration of gas in the fountain. As an alternative example 2 is based on the same initial situation, but for a starburst of half the intensity and twice the duration compared with example 1. The vertical velocity of gas in the fountain then is considerably slower. Example 3 describes a high general supernova rate of 10 per Millenium with 1 kpc of the Galactic center. This results in a rather thick and fluffy gas disk. More half a million years a starburst occurs with 10 supernovae per Millenium within 400 pc of the Galactic center.

We find that though positrons can be efficiently convected to large heights above the disk, they will in general not produce a very strong annihilation signal there. As an example we show in Figure 1 the vertical distribution of positron and annihilation line flux for example 1.
The typical hydrodynamical outflow in our simulations resembles a narrow cone located exactly above the Galactic center. The initial density field times the gradient of the gravitational potential $\rho \nabla \Phi$ actually confines the flow, which then rapidly accelerates as it moves outwards. In contrast to the idealized flow envisaged by Dermer and Skibo, the positrons are not injected in a pre-existing flow, but co-spatial with the pressure input. Therefore only a fraction of them will be convected to large heights above the plane. The bulk of positrons annihilates in the disk.

In our simulations the typical gas density between 0.5 kpc and 1 kpc above the Galactic plane is $10^{-2}$ cm$^{-3}$. The material has temperatures in excess of $10^6$ K, so that the annihilation rate is $\sim 10^{-16}$ sec$^{-1}$. This implies that the life time of positrons is considerably longer than the duration of a supposed starburst.

As a result the positrons supplied by the starburst will have a strongly reduced impact on the spatial distribution of annihilation line emission compared with the naive estimates. In example 1 the ten thousand supernovae of the starburst result in a high-latitude ($z > 400$ pc) afterglow of 511 keV line emission with a flux of $3 \cdot 10^{-5}$ cm$^{-2}$ sec$^{-1}$, which is 5% of the total 511 keV flux 1 Myr after the starburst has ceased. This is an order of magnitude less than the observed high-latitude flux, which is about 50% of the total 511 keV line emission from the Galactic center region.
We have so far not considered dust at large heights above the Galactic plane. Zurek (1985) suggested that dust grains may in fact be quite efficient annihilation sites. Dust expelled by the supernovae and their progenitor winds may provide annihilation rates considerably higher than the $\sim 10^{-16}$ sec$^{-1}$ achieved in our simulations at locations between 0.5 kpc and 1.5 kpc above the Galactic plane.

Summary
In this paper we have investigated in detail the fountain model for the extraplanar 511 keV line emission observed with OSSE. If the outflow is caused by starburst activity, the supernovae would provide both the positron injection and the input of heat and kinetic energy into the ISM. We have build a two-dimensional code to follow the development of a hydrodynamical fountain in the Galactic center region. We have then calculated the transport, cooling, and annihilation of positrons as test particles in the outflow.

We find difficulties with the fountain model if the positrons are produced by supernovae in a starburst near the Galactic center. Even when a strong one-sided outflow of hot gas is established and positrons are effectively transported to a distance of 1 kpc above the Galactic plane, the efficiency of annihilation in this region is very low. Almost all of the positrons would annihilate close to the Galactic plane, and thus they would contribute only little to the high latitude feature of 511 keV line emission.

Annihilation on dust grains may increase the 511 keV line flux at high latitudes. Alternatively the observed positrons may not be entirely produced by supernovae. Possible sources of positrons includes black holes or a $\gamma$-ray burst, which would have to be located above the Galactic center. It can also not be excluded that the high latitude structure is of local origin, e.g. from Gould’s belt, and not associated with the Galactic center. In this case we would expect that high latitude 511 keV line emission is also observable from other directions.

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