PARTICLE ACCELERATION IN (BY) ACCRETION DISCS

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ABSTRACT

I present a model for acceleration of protons by the second-order Fermi process acting on randomly scrambled magnetic flux arches above an accretion disc. The accelerated protons collide with thermal protons in the disc, producing degraded energetic protons, charged and neutral pions, and neutrons. The pions produce gamma-rays by spontaneous decay of $\pi^0$ and by bremsstrahlung and Compton processes following the decay of $\pi^\pm$ to $e^\pm$.

INTRODUCTION

The most remarkable property of AGNs is the appearance, in many cases, of much of their luminosity as the acceleration of nonthermal particles. Evidence for this consists of the polarized optical continuum with a power law spectrum found in some AGN, the great power required to supply radiating electrons to radio galaxies, and the gamma-ray luminosity of $10^{48}$ erg/sec of 3C279 recently discovered by GRO.

This paper is a preliminary account of the calculation of a model of particle acceleration in low density astronomical shear flows. Particles are accelerated by a second-order Fermi mechanism. They are assumed to be trapped in magnetic mirrors consisting of magnetic flux arches whose feet are pinned to the surface of a quasi-Keplerian accretion disc. The differential motion of points on the disc surface at differing radii accelerates the particles. The resulting forces on the disc (acting through the magnetic field) are described by a viscosity, and may be its chief dissipative process. This mechanism directly converts the gravitational power of black hole accretion to particle acceleration. Although this process is second order in the Keplerian velocity, in rapidly rotating inner discs it may be rapid.

CALCULATION

The greatest uncertainty of this model is the magnetic field configuration, particularly how flux tubes connect disc points at different radii. This uncertainty is not presently resolvable empirically or theoretically. In addition, it is not known how well the magnetic arches act as mirrors, nor is the density distribution of thermal gas within and above the disc known. The accelerated protons collide with the gas (the interaction of GeV protons with radiation is negligible,
but Compton scattering prevents the acceleration of electrons). These uncertainties affect both the acceleration rate and the loss rate, and may be combined into a single parameter describing the ratio between these two rates.

The evolution of the isotropic volume-averaged proton distribution function in momentum space $n(p)$ is given by

$$\frac{\partial n(p)}{\partial t} = \vec{\nabla}_p \cdot [D(p) \vec{\nabla}_p n(p)] - \rho \sigma(p) v(p)n(p) + \rho \int v(p') \sigma(p', p)n(p') dp'; \quad (1)$$

on the right hand side the first term represents the momentum space diffusion, the second represents collisional losses in thermal matter of density $\rho$, and the third represents the contribution of collision products to the proton distribution. The velocity $v(p) = p/\sqrt{m_p^2 + p^2/c^2}$ and $\sigma(p)$ and $\sigma(p', p)$ are total and differential proton-proton cross-sections. If the momentum-space diffusion results from scattering by magnetic mirrors with uncorrelated speed $u$ and has a mean scattering length $\ell$, then

$$D(p) = \frac{4}{3} \frac{u^2}{\ell c^2} p E, \quad (2)$$

where the coefficient has an order-of-unity uncertainty resulting from the unspecified correlation between the directions of the incident and scattered particles. The parameter $\rho \ell$ describes the comparative importance of acceleration and collisional losses.

The scattering processes are

\begin{align*}
    p + p &\rightarrow p + p \quad (3a) \\
    p + p &\rightarrow p + p + \pi^0 \quad (3b) \\
    p + p &\rightarrow p + n + \pi^+ \quad (3c) \\
    p + p &\rightarrow \text{others} \quad (3d)
\end{align*}

A characteristic energy scale is set kinematically by $m_p c^2 = 938$ MeV, and also by the increase and saturation of the cross-sections for the inelastic processes (3b) and (3c) in the range 400–700 MeV. At laboratory energies $> 1$ GeV (3d) begins to replace (3b) and (3c), but was not included in these preliminary calculations (although the correct total inelastic cross-section was used).

The calculations reported here consisted of the evolution of equation (1), using (2), and the calculation of the spectrum of $\pi^0$ produced in (3b) and of the subsequent decay gamma-rays. The spectrum of $\pi^+$ was not calculated (although the cross-section of [3c] was included in equation [1]); this important process (its cross-section is about five times that of [3b]), as well as the subsequent decay $e^+$, and the effects of (3d) are presently being added to the code. The differential cross-sections used were scaled from the measurements of Bugg, et al. at 970 MeV; this is one of the few experimental papers which give the
laboratory distribution of the energies of the scattering products (most of the literature gives center-of-momentum energies, which are insufficient unless the scattering angle is also known).

RESULTS

The effect of (3a) is to multiply the number of energetic protons, while conserving their total kinetic energy. Processes (3b)–(3d) have a similar effect, although some kinetic energy is lost. The fate of the neutron produced in (3c) depends on the dimensions of the acceleration region; in regions larger than $10^{13}$ cm (appropriate to a massive black hole in an AGN) it decays and may be regarded as equivalent to a proton, while neutrons are lost from smaller regions (galactic X-ray sources).

Momentum space diffusion multiplies the energetic proton energy, while reducing their number (some diffuse to a Coulomb drag sink at zero momentum). The combination of diffusive acceleration and collisional loss will, for suitable values of $\rho \ell$, lead to an exponential (in time) runaway in proton number and energy density, with a stationary normalized spectrum. In reality such a runaway would saturate because the growing particle energy density would disrupt the confining magnetic field, or because the growing viscosity would deplete the accretion flow.

The following figures show the results of such a calculation. Particles up to 6 GeV were included, but cross-sections above about 1 GeV were inaccurate because of the exclusion of (3d). The calculated maximum in the gamma-ray spectrum at $m_{\pi^0}c^2/2$ was not observed in the data\textsuperscript{1}. This may perhaps be explained by the contribution of gamma-rays from $e^\pm$ bremsstrahlung, as is the case for the Galactic gamma-ray spectrum. These processes will be included in the future.

REFERENCES

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Figure 1: Proton spectrum.
Figure 2: Neutral pion spectrum.
Figure 3: Gamma-ray spectrum from neutral pion decay.
