Revista Mexicana de Astronomía y Astrofísica, **27**, 107-110 (1993)

COSMIC RAYS IN AGNs

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RESUMEN

Obtenemos límites para el flujo de rayos cósmicos en AGNs investigando los mecanismos de aceleración en un ambiente activo y considerando la propagación de rayos cósmicos desde los AGNs hasta nuestra Galaxia. Es comúnmente aceptado que el flujo observado, con energías inferiores a 10^{19} eV, es de origen Galáctico; por consiguiente, el flujo que proviene de todos los AGNs debe ser mucho menor que el flujo observado. Demostramos que luminosidades de rayos cósmicos con valores entre 10^{43} y 10^{46} ergs/s son permitidas por modelos de ley de potencia admisibles en AGNs. Por tanto, el flujo de rayos cósmicos intrínseco puede ser suficiente para afectar significamente el gas circundante, el cual forma las regiones de líneas anchas y líneas estrechas.

ABSTRACT

We obtain constraints on the cosmic ray flux in AGNs by investigating the acceleration mechanisms in an active environment and by considering the propagation of cosmic rays from AGNs to our Galaxy. At energies below 10^{19} eV, the observed flux is thought to be mostly of Galactic origin; therefore, the flux coming from all quasars must be much less than the observed flux. We show that cosmic ray luminosities at each AGN with values between 10^{43} and 10^{46} ergs/s are still allowed, for plausible power-law models. Thus, the intrinsic flux of cosmic rays can be large enough to affect significantly surrounding gas in the broad and the narrow line regions of an AGN.

Key words: **ACCELERATION OF PARTICLES — GALAXIES: ACTIVE**

1. INTRODUCTION

Observations of cosmic rays on Earth show that the cosmic ray spectrum is approximately a composition of three power-laws (Watson, 1991). The first two components usually are associated with Galactic cosmic rays. In the energy range from 10^9 to 10^{15} eV, cosmic rays supposedly are accelerated in supernova remnants. At energies between 10^{15} and 10^{19} eV, the cosmic rays probably are accelerated in sources of a different nature, and we may be observing a superposition of several spectral forms (Axford, 1991). At energies higher than 10^{19} eV, a third power-law is observed, and it usually is associated with cosmic rays of extragalactic origin. These cosmic rays are likely to come from nearby radio galaxies (Takahara, 1991; Begelman & Kirk, 1990). The fact that a Greisen & Zatsepin cutoff is not observed rules out the possibility that the extragalactic cosmic rays are coming from distant quasars (Berezinsky & Grigor'eva, 1988; Biermann, 1991). However, even though cosmic rays from quasars (or AGNs in general) do not contribute much to the observed cosmic ray spectrum, they are likely to be present in the AGN in significant amounts, and interact with the local gas. Therefore, we are interested in obtaining a reasonable value for the flux of cosmic rays accelerated within an AGN in order subsequently to investigate its effect on the gas.

2. THE LUMINOSITY RATIO

In our Galaxy, the radiation luminosity in the visible and infrared range is about 5×10^{43} ergs/s. This luminosity is associated with starlight and star formation, so it is proportional to the supernova abundance, which in turn is related to the Galactic cosmic ray production. Integrating the observed cosmic ray flux from 10^9 to 10^{19} eV, we obtain a cosmic ray luminosity of 2×10^{41} ergs/s. This means that the L_{CR} to L_R ratio is approximately 10^{-2}.

In radio galaxies, the acceleration of cosmic rays is thought to arise in hot spots in the radio lobes (Begelman & Kirk, 1990). Thus, in this case, it is the radio luminosity, which has a typical value of 10^{44} ergs/s, that should be compared with the cosmic ray luminosity. This cosmic ray luminosity is calculated by assuming that nearby radio galaxies are the dominant source of observed cosmic rays with $E > 10^{19}$ eV. The value obtained is $L_{CR} \leq 10^{42}$ ergs/s, which, again, leads to a L_{CR} - L_{rad} ratio of about 10^{-2}.

What happens if we apply this same ratio for AGNs (mostly Seyferts 1 and quasars)? Since the radiation luminosity is typically between 10^{45} and 10^{48} ergs/s, the attendant cosmic ray luminosity would vary from 10^{43} to 10^{46} ergs/s. Here, we use the radiation luminosity corresponding to the ultraviolet and the X-ray range, because is associated with the central region, where most of the cosmic rays are likely to be accelerated in the AGN (without considering the powerful radio galaxies, which contain hot spots in the extended radio lobes, far from the nucleus).

3. ACCELERATION MECHANISMS IN AGNs

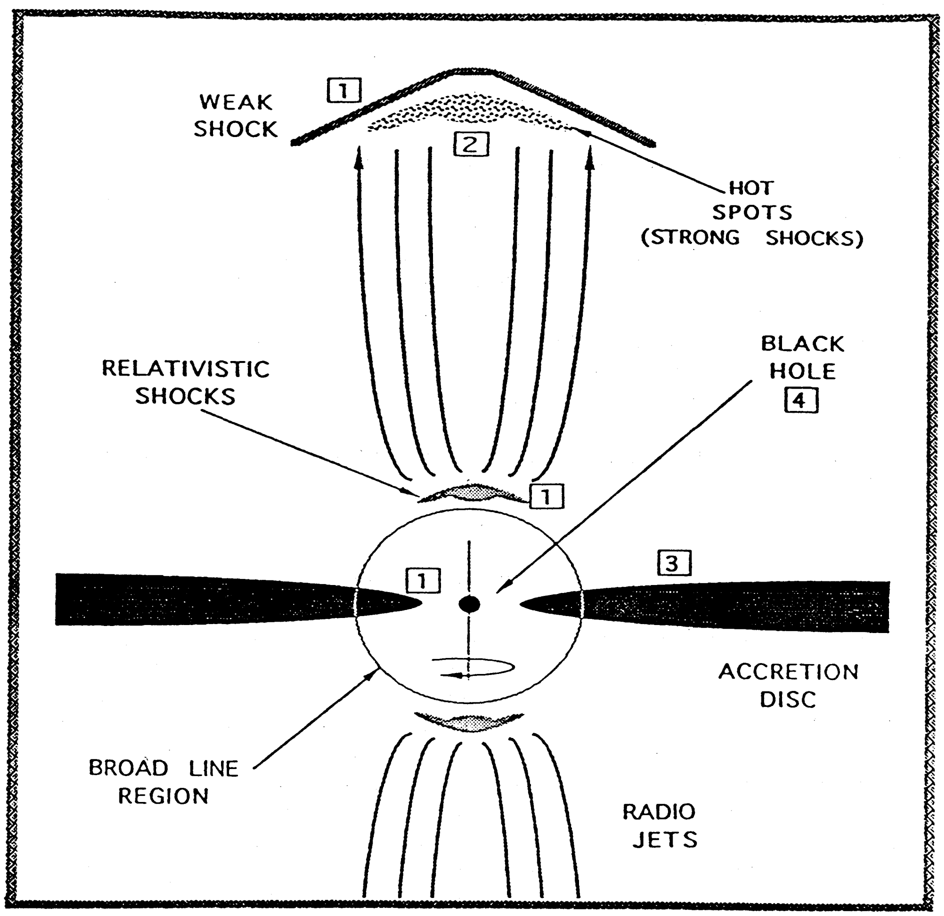

Fig. 1. — Regions of particle acceleration in a general AGN. The numbers in the Figure correspond to the different acceleration mechanisms presented in the Table below.

Mechanism	Characteristics	Location
First Order Fermi (1) Particle gains energy recrossing a shock front by scattering with magnetic turbulence near the shock.	Efficient when magnetic field is perpendicular to the flow.	In shocks formed by infalling or ejected material, in the inner part of the accretion region.
	Spectrum of accelerated particles is $dN(E) \propto E^{-2}$ for strong shocks and can be flatter for relativistic shocks.	In shocks formed in radio jets, due to the interaction with the intergalactic medium.
Shock-Drift (2) Particle gains energy as its gyrocenter crosses a shock front, by drifting parallel to the electric field.	Efficient when magnetic field is parallel to the flow.	In oblique shocks formed by superluminal flows, which are associated with the hot spots in radio lobes (mostly in radio galaxies).
	Acceleration to very high energies: $10^{18} \leq E \leq 10^{20}$ eV.	
Direct Acceleration (3) Particle is accelerated by the electromagnetic field of the accretion disk, in regions where the magnetic energy has built up due to both rotation of the disk and coupling of the field with the plasma.	Acceleration to energies $\sim 10^{20}$ eV.	In the edge of the accretion disk (near the corona), where the density is lower and particles can escape from the disk.
Penrose Process (4) Particle gains energy falling in the ergosphere of a rotating black hole, and splitting in two, in such a way that one piece goes down to the black hole (with negative energy) and the other piece escapes with larger energy than initially.	Very unlikely. Probably not important in an AGN environment.	Near the black hole.

4. PROPAGATION OF COSMIC RAYS FROM AGNs TO EARTH

If each AGN injects into intergalactic space a cosmic ray flux such that

$$F(\epsilon) = K(\epsilon_o/\epsilon)^{-\alpha} \quad \epsilon_{min} < \epsilon < \epsilon_{max} \ ,$$

then, the summed flux received on Earth is (Hill and Schramm, 1985)

$$j(E) = \frac{3}{8\pi} n_0 R_0 K(E_o/E)^{\alpha} \frac{1}{m - \alpha - 1/2}[(1 + z_{max})^{m-\alpha-1/2} - 1] \ , \quad E < E_{max}/(1 + z_{max})^2$$

$$j(E) = \frac{3}{8\pi} n_0 R_0 K(E_o/E)^{\alpha} \frac{1}{m - \alpha - 1/2} [(E_{max}/E)^{m/2-\alpha/2-1/4} - 1] \quad , \quad E_{max}/(1+z_{max})^2 < E < E_{max}$$

Here, n_0 and R_0 are, respectively, the AGN number density and the Hubble radius at present, z is the redshift and m is the AGN luminosity evolution parameter. The energy E_{min} corresponds to the minimum energy of particles that can escape from the quasar, i.e., those whose gyroradii are larger than the AGN central region. For a magnetic field of $B_{AGN} \simeq 10^{-5}G$), its value is $E_{min} \sim 10^{17}$ eV. The energy E_{max} is approximately 10^{19} eV; particles with higher energy are destroyed in the AGN itself via photomeson and pair production processes. These are particularly efficient because of the large photon number density in the AGN central region. The AGN luminosity evolution is taken to be

$$L \propto (1+z)^m \quad \text{with} \quad m = 3.2 \quad ,$$

because this model agrees well with observations (Boyle et al, 1990). Finally, the upper limit for the redshifts of observed AGNs used in our calculations is $z_{max} = 5$.

5. RESULTS AND CONCLUSIONS

As noted above, we are interested only in summed AGN cosmic ray fluxes that are significantly below the observed flux, since the latter is mainly Galactic for E< 10^{19} eV. We find that if the (injected) AGN flux has $\alpha = 1.7$, the cosmic ray luminosity of each AGN must be lower than $L_{CR} \simeq 10^{44}$ ergs/s, in order to not contradict the observations. If $\alpha = 2$, $L_{CR} \leq 10^{45}$ ergs/s, and if $\alpha = 2.3$, $L_{CR} \leq 10^{46}$ ergs/s. The most likely acceleration mechanism in AGNs is first order Fermi acceleration in relativistic shocks (the most likely in an AGN environment), so the most suitable models are those with α between 1.7 and 2. These results change significantly when z_{max} and E_{max} are increased because the cosmic ray flux received from AGNs then is much larger. However, they do not change much with variations in m or E_{min}.

Thus, we believe that relatively large cosmic ray fluxes can and do exist in AGNs. Such fluxes need not contradict the observed cosmic ray spectrum and are consistent with the most probable acceleration mechanisms. Further constraints may be found from a study of the interaction between cosmic rays and the AGN gas. Cosmic rays induce spallation reactions in the narrow line region, producing B, Be and Li, and heat broad line region clouds, changing the chemistry in their interior. These issues are now under investigation.

This research is supported by National Science Foundation grant PHY-9024397 to Rice University, and by a fellowship award (to M. C.) from the Spanish Ministry of Education and Science.

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