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DIFFUSE HARD X-RAY AND GAMMA-RAY EMISSION FROM M87

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ABSTRACT

Radio measurements are used to infer the relativistic electron distributions in the central and halo regions of M87. From these distributions and the inferred relativistic proton components, we predict the hard X-ray and gamma-ray spectrum of M87, taking into account all relevant radiative processes. We discuss the feasibility of measuring the high-energy spectrum of M87 with the High Energy Gamma-Ray Telescope (Egret) onboard the Gamma Ray Observatory (GRO). Comparison of our calculation with present gamma-ray flux upper limits leads to a lower limit of 1.5 μG on the mean value of the halo magnetic field.

Subject headings: galaxies: individual (M87) — galaxies: X-rays — gamma-rays: general — interstellar: magnetic fields

I. INTRODUCTION

The giant elliptical M87 is the largest and, in many ways, the most interesting nearby galaxy. Its location close to the center of the Virgo Cluster and its very high mass ($\sim$6–8 $\times 10^{13}$ $M_\odot$ within 90′ of the optical center; Fabricant and Gorenstein 1983) render it very important to the cluster dynamics. M87 has been extensively studied in radio, optical, and soft X-ray regions of the electromagnetic spectrum. Relatively little is known about its high-energy photon spectrum, other than gamma-ray flux upper limits (Fichtel *et al.* 1978; Pollock *et al.* 1981) and a hard X-ray *HEAO 1* detection (Lea *et al.* 1981) which, however, may be due to emission from a compact source at its center (see § II).

An investigation of diffuse, nonthermal high-energy phenomena in M87 is of interest from various points of view. In general, analyses of nonthermal emission mechanisms further our understanding of the basic properties of magnetic fields and relativistic electrons and protons. Thus a comparison of the predicted high-energy spectrum with measurements leads to a determination of the mean value of the magnetic field in the central region and halo of M87. This is useful as our knowledge of the magnetic field in halos is very poor. Knowing the density and energy spectrum of relativistic electrons and protons will provide significant input to theories of particle acceleration. Moreover, it will allow a more precise assessment of the contemplated role these particles play in the thermal balance of the hot gaseous halo (Rephaeli 1979, 1987; Dennison 1980*a*; Tucker and Rosner 1983). This information is relevant to estimates of mass accretion onto the core of M87 through cooling flows (Stewart *et al.* 1984; see also the review by Fabian, Nulsen, and Canizares 1984). A study of the high-energy spectrum of M87 may also contribute to the resolution of the origin of cosmic rays (CR) in our local supercluster neighborhood.

In this paper, we construct a model for the relativistic particle spectra of M87 that is closely based on radio observations of the central and halo regions. Using these particle spectra we calculate the predicted high-energy photon spectrum due to all relevant radiative processes. Comparison of the results with the *SAS 2* and *COS B* upper limits determines a lower limit to the value of the mean halo magnetic field $B^h{}_{\mu G}$ (in microgauss). More will be learned when the results of analyses, such as the one presented here, are compared with more sensitive planned experiments. Indeed, it is the improved sensitivity of future experiments, such as Egret onboard GRO, which motivates our work here.

II. OBSERVATIONS OF M87

Radio observations of M87, separated into contributions from a central region of a few kpc radius and a halo of $\sim$40 kpc in extent, are shown in Figure 1 (Andernach *et al.* 1981 and references therein; Kotanyi 1982). Values for the total (central region + halo) radio emission at 10 MHz (Clark 1967; cf. Lea *et al.* 1981) and 26.3 MHz (Viner and Erickson 1975) are also shown. The total radio flux from M87 is well represented by a power law with energy spectral index $\alpha \approx 0.8$. Note that the radio emission in the central region cannot arise from an extremely compact nuclear source, as frequencies $\nu < 10$ GHz will be strongly self-absorbed in regions smaller than $\sim 10^{16}$ cm and with magnetic field $\gtrsim 10$ μG.

Optical emission from M87 is dominated by starlight. Fabricant and Gorenstein (1983) give a value for the optical luminosity within 10′ of M87, corresponding roughly to the extent of the radio halo, of $L_{\rm opt}(10') \approx 5.8 \times 10^{10}$ $L_\odot$, where $L_\odot$ is the solar luminosity. Representing the optical emission as a dilute blackbody peaking at 5000 Å and using $d = 20$ Mpc as the distance to M87, an optical energy density $\rho_{\rm opt}(10') \approx 0.25\rho_{\rm bb}$ is implied, where $\rho_{\rm bb} = 0.25$ eV cm^{-3} is the energy density of the cosmic microwave background radiation (CMB).

M87 has been well-studied in X-rays and was, in fact, the first identified extragalactic X-ray source (see Sarazin 1986 for a review of cluster X-ray emission). High-resolution X-ray maps of the Virgo Cluster show that the emission is centered on M87 (Schreier, Gorenstein, and Feigelson 1982; Feigelson *et al.* 1987). Soft X-ray emission from the halo comes from $\sim 3 \times 10^{12}$ $M_\odot$ of hot gas with temperature $T \approx$ few keV (Fabricant and Gorenstein 1983). Emission above 10 keV (Lea *et al.* 1981; see Fig. 2) cannot be accounted for by a single-

TABLE 2D—*Continued*

Star	X	Y	V	σ_V	(B−V)	$\sigma_{(B-V)}$	(U−B)	$\sigma_{(U-B)}$	(V−R)	$\sigma_{(V-R)}$
215	134.76	456.17	18.64	0.01	0.09	0.02	-0.27	0.01	-0.03	0.03
216	137.69	469.58	19.75	0.01	0.78	0.02	...	...	0.50	0.02
217	307.09	470.14	21.69	0.13	...	...	...	...	0.40	0.34
218	238.60	470.17	20.77	0.06	0.41	0.08	...	...	-0.05	0.10
219	298.57	474.78	22.54	0.10	1.38	0.17	...	...	...	...
220	50.67	475.13	21.35	0.07	0.61	0.09	...	...	...	...
221	28.36	477.14	21.46	0.10	0.44	0.13	...	...	...	...
222	215.64	480.60	20.14	0.03	...	...	...	...	0.78	0.04
223	43.11	486.67	21.41	0.11	0.02	0.12	...	...	...	...
224	171.73	487.36	20.28	0.03	0.41	0.04	-0.40	0.05	0.01	0.05
225	28.94	493.42	21.03	0.08	...	...	...	...	0.77	0.09
226	171.51	500.18	20.80	0.06	...	...	...	...	0.80	0.08

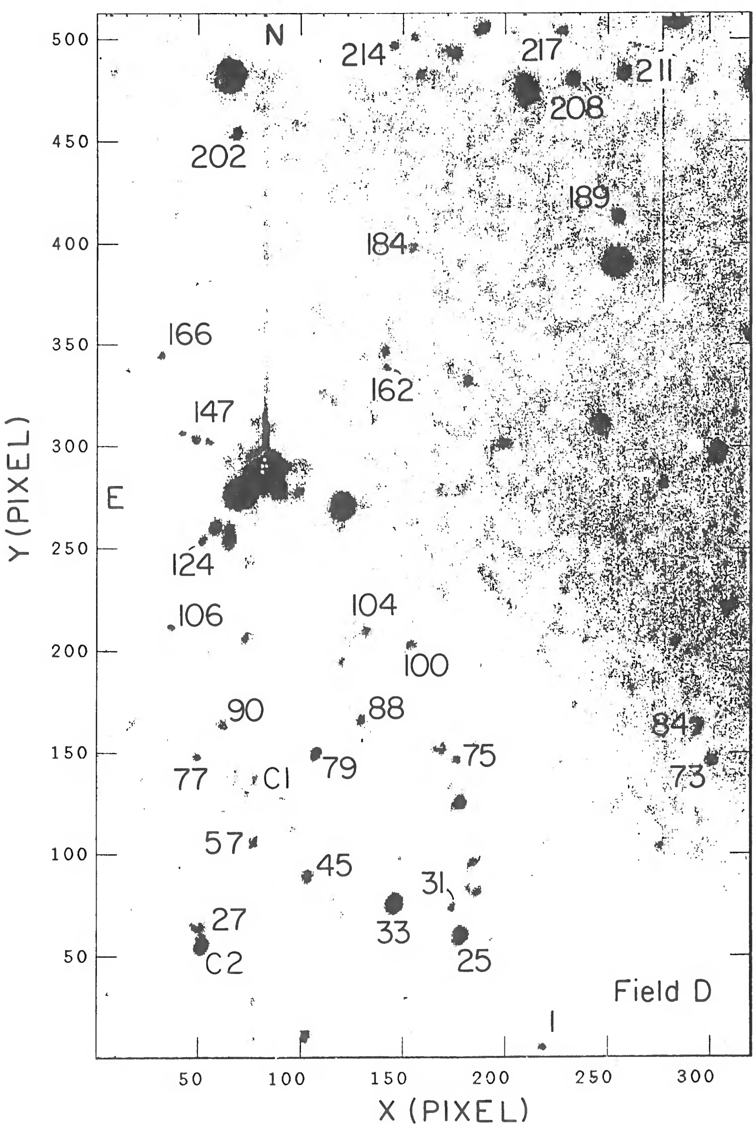

FIG. 3.—Field D. C1 and C2 are newly discovered young open clusters.

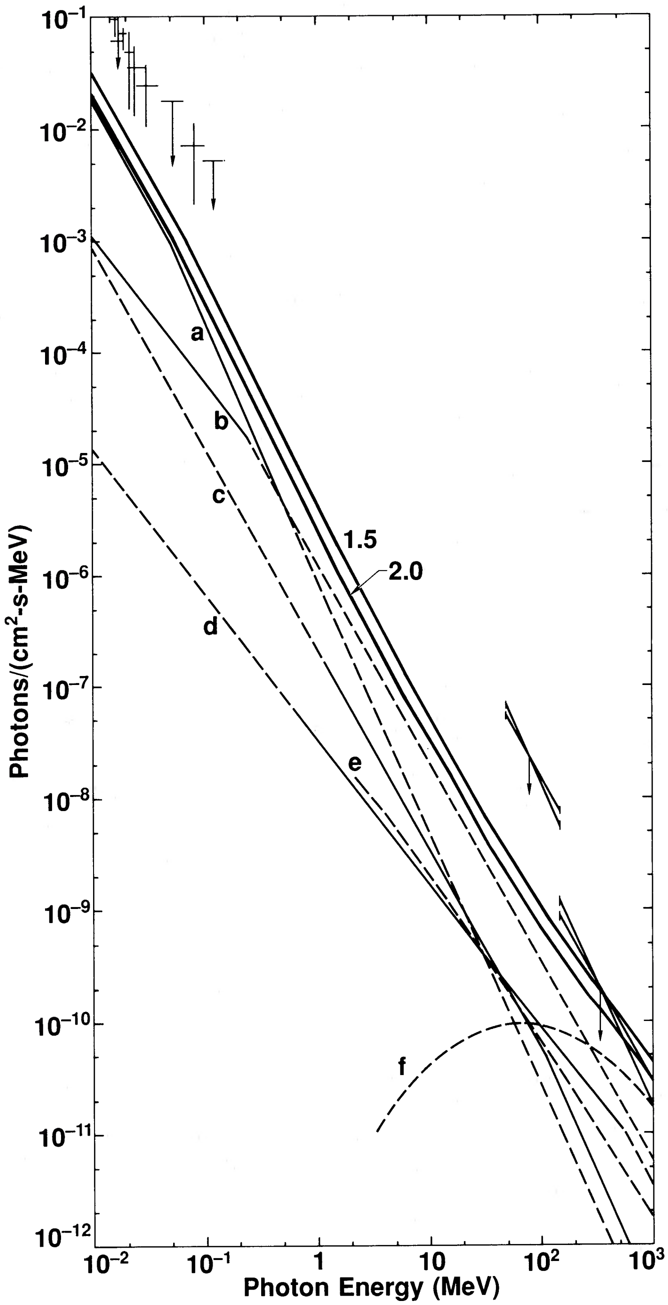

FIG. 2.—Model predictions of X-ray and γ-ray flux from M87. The heavy solid lines represent the model predictions for the total flux and are labeled by values of the mean halo magnetic field in microgauss. The separate contributions to the total flux for $B^h{}_{\mu G} = 2.0$ are shown by the light lines and represent halo (*a*) and central region (*b*) electrons Comptonizing CMB, halo (*c*) and central region (*d*) electrons Comptonizing optical radiation field, bremsstrahlung emission (*e*) from central region electrons, and neutral pion decay gamma radiation (*f*) from protons in the central region. Dashed light lines represent fluxes deduced from extrapolations of particle spectra not directly inferred from radio synchrotron observations. Hard X-ray data points below 100 keV are from Lea *et al.* (1981) and *COS B* upper limits are from Pollock *et al.* (1981).

the average residence time τ of particles in the central region of M87 is energy-independent.

It is assumed that electrons are injected into the central region of M87 and then diffuse into the halo, losing energy primarily through Compton and synchroton processes. The steady-state energy distribution of the electrons in the central region is obtained by solving the continuity equation, giving

$$N_c(\gamma) = \frac{q_0(b_c\tau)^{\Gamma-1}}{b_c\gamma^2} \exp(-u) \times \sum_{i=0}^{\infty} \frac{u^{\Gamma-1+i}}{(\Gamma-1+i)i!} \rightarrow \begin{cases} \tau q_0\gamma^{-\Gamma}, & \gamma \ll (b_c\tau)^{-1} \\ \dfrac{q_0\gamma^{-(\Gamma+1)}}{b_c(\Gamma-1)}, & \gamma \gg (b_c\tau)^{-1} \end{cases} \quad (1)$$

(cf. eq. [5.14] of Blumenthal and Gould 1970). In this equation, $Q_c(\gamma) = q_0\gamma^{-\Gamma}$ [electrons s^{-1} γ^{-1}] is the electron source spectrum characterized by spectral index Γ, $u = 1/b_c\gamma\tau$, $b_c = 1.3 \times 10^{-20}$ $(w^c + 0.1B^c{}_{\mu G}{}^2)$, where w^c is the average photon energy density in the central region in units of 0.25 eV cm^{-3}, and $B^c{}_{\mu G}$ is the mean magnetic field in the central region in microgauss. The injection of electrons into the halo is given by the source function $N_c(\gamma)/\tau$. Assuming that the halo electrons lose energy through Compton scattering and synchrotron emission before escaping into intracluster space, the steady state intensity of the halo electrons is given by

$$N_h(\gamma) = (b_h\tau\gamma^2)^{-1} \int_\gamma^\infty d\gamma' N_c(\gamma') \rightarrow \begin{cases} \dfrac{q_0\gamma^{-(\Gamma+1)}}{b_h(\Gamma-1)}, & \gamma \ll (b_c\tau)^{-1} \\ \dfrac{q_0\gamma^{-(\Gamma+2)}}{\tau b_c b_h \Gamma(\Gamma+1)}, & \gamma \gg (b_c\tau)^{-1}. \end{cases} \quad (2)$$

Here b_h is the loss coefficient defined above, but now with values appropriate to the halo.

If electrons are injected into the central region with $\Gamma = 1.6$, the steady state electron distribution will break from 1.6 to 2.6 at $\gamma_c = (b_c\tau)^{-1}$, producing a change in spectral index of the radio flux at a frequency $\nu_c \approx 2.8B^c{}_{\mu G}\gamma_c{}^2$ from $\alpha \approx 0.3$ at $\nu \ll \nu_c$ to $\alpha \approx 0.8$ at $\nu \gg \nu_c$. The spectrum of electrons escaping into the halo will be steepened by one unit due to Compton and synchrotron losses, producing a halo radio spectrum that breaks from $\alpha \approx 0.8$ at $\nu \ll \nu_c$ to $\alpha \approx 1.3$ at $\nu \gg \nu_c$. This behavior is roughly in accord with observations, as shown in Figure 1. We have used the asymptotic forms of the observed radio spectra to provide relations among the various quantities characterizing the model. The basic equation relating the observables is the energy flux

$$F_\nu[\text{ergs cm}^{-2}\ \text{s}^{-1}\ \text{Hz}^{-1}] = \frac{\alpha_f h\nu}{d^2}\left(\frac{3}{2}\right)^{(p-1)/2} Ka(p)\left(\frac{\nu_B}{\nu}\right)^{(p+1)/2} \quad (3)$$

(e.g., Rephaeli 1979; Gould 1979), where α_f is the fine-structure constant, $N(\gamma) = K\gamma^{-p}$ is the steady state electron spectrum, ν_B is the electron gyrofrequency, and the values $a(p)$ are tabulated (e.g., Blumenthal and Gould 1970).

Since $w^h = 1.25$ (§ II), all quantities are known once a value for $B^h{}_{\mu G}$ is chosen. In particular, we find that

$$B^c{}_{\mu G} = 1.9B^h{}_{\mu G}, \quad (4)$$

$$b_c = 3.3b_h, \quad (5)$$

and

$$q_0[s^{-1}] = 2.9 \times 10^{46}\, \frac{d^2{}_{20}(b_c/1.3 \times 10^{-20})}{B^{c\,1.8}_{\mu G}}, \quad (6)$$

where d_{20} is the distance to M87 in units of 20 Mpc. We numerically integrated the exact steady state distribution of electrons in the halo and central region, equations (1) and (2), assuming an isotropic pitch-angle distribution of electrons. The results are shown by the solid curves in Figure 1 for the case $B^h{}_{\mu G} = 1.5$, and are nearly indistinguishable from the results of a calculation with $B^h{}_{\mu G} = 2.0$. The agreement between the model calculation and data is better than 40% for all points except the 10.7 GHz point with large error bars and is adequate for the estimates of γ-ray emission to be made.

Finally, the limited meaining of relation (4) should be realized. This equation relates the effective mean value of the field in the central ($\sim 1'$) region to that in the halo ($\sim 7'$) region, weighted by the strength of the synchrotron emissivity. Our treatment neglects detailed effects of electron propagation in a magnetic field that is likely to be nonuniform. For a discussion of the effects of spatial variations of the magnetic field and electron distributions, see Rephaeli (1977, 1979).

IV. PREDICTED SPECTRA

Electrons emitting synchrotron radiation will produce X-rays and γ-rays by Comptonizing CMB and optical photons. The Comptonized photon flux [photons cm^{-2} s^{-1}]

$$\phi_C(\epsilon) = \frac{\xi K}{4\pi d^2}\left(\frac{r_e^2}{\pi \hbar^3 c^2}\right)(kT_{\rm rad})^{(p+5)/2}F(p)\epsilon^{-[(p+1)/2]} , \quad (7)$$

where $T_{\rm rad}$ is the effective temperature and ξ is the dilution factor of the radiation field. Values of $F(p)$ can be found in the paper by Blumenthal and Gould (1970). In Figure 2 we show the separate Compton fluxes due to halo and central region electrons Comptonizing CMB and optical photons for the case $B^h{}_{\mu G} = 2.0$. We also calculated the bremsstrahlung flux produced by electrons colliding with particles in the central region of M87. For this calculation it was necessary to assume a particle density in the cental region of M87 and to solve the continuity equation including electronic excitation (ionization) and bremsstrahlung losses (see Gould 1975 for a summary of these loss rates). Letting $n_e = 0.2$ cm^{-3} in analogy to our own Galaxy, we numerically integrated the equation

$$\phi_{\rm ff}(\epsilon) = \frac{2n_e c}{4\pi d^2}\int_{1+x}^{\infty} d\gamma N(\gamma)\frac{d\sigma(\epsilon, \gamma)}{d\epsilon} , \quad (8)$$

where

$$\frac{d\sigma}{d\epsilon} = \frac{2\alpha_f \sigma_T}{\pi\epsilon}\left(1 - \frac{x}{\gamma} + \frac{3x^2}{4\gamma^2}\right)\ln\left[\frac{2\gamma^2[1-(x/\gamma)]}{ex}\right], \quad (9)$$

$x = \epsilon/m_e c^2$, and $e = \exp(0.5) \approx 1.649$ (Blumenthal and Gould 1970). The result, shown for $B^h{}_{\mu G} = 2.0$ by curve (*e*) in Figure 2, does not make a significant contribution to the γ-ray flux. A similar calculation for the bremsstrahlung emission from halo electrons, using $n_e \approx 0.003$ cm^{-3} (Fabricant and Gorenstein 1983), yields fluxes at least a factor of 2 below the bremsstrahlung flux from the central region and can be neglected.

The gamma-ray flux from neutral pion decay is given by

$$\phi_{\pi^0}(\epsilon) = \frac{cn_e}{4\pi d^2}\int_{\gamma_{p\min}}^{\infty} d\gamma_p \beta_p\left(\frac{dN}{d\gamma_p}\right)\frac{d\sigma_\pi(\gamma_p, \epsilon)}{d\epsilon} , \quad (10)$$

where γ_p is the proton Lorentz factor and $\gamma_p{}^{\min}$ is the minimum value of γ_p which yields a photon with energy ϵ. We integrated equation (10) using calculations of the differential γ-ray production cross section $d\sigma_\pi/d\epsilon$ (Murphy, Dermer, and Ramaty 1987). The normalization of the steady state proton spectrum $dN/d\gamma_p$ was determined by assuming that at 1 GeV kinetic energy, the ratio of the proton and electron fluxes in the central region of M87 is about 30, as in our Galaxy (e.g., Ormes and Freier 1978). Thus

$$\frac{dN}{d\gamma_p} = 30 f_{30}\, q_0\, \tau\left(\frac{m_e}{m_p}\right)^{\Gamma-1}\gamma_p{}^{-\Gamma} . \quad (11)$$

The result of this calculation for $B^h{}_{\mu G} = 2.0$ is shown in Figure 2 by curve (*f*).

The bremsstrahlung γ-ray emissivity from charged pion decay electrons and positrons in the central region is small compared to the neutral pion-decay contribution and can be neglected, as the pion-decay electrons and positrons escape from the central region before radiating most of their energy. We also neglect neutral pion decay emission from the collisions of protons with particles in the halo. Even if the protons diffuse out at the Alfvén speed of ~ 100 km s^{-1}, only a very small fraction of the protons will undergo a pion-producing collision before escaping from the halo.

V. RESULTS AND DISCUSSION

Figure 2 shows the total X-ray and gamma-ray flux implied by our model of M87, assuming $B^h{}_{\mu G} = 1.5$ and 2.0. Values of $B^h{}_{\mu G} \lesssim 0.5$ are inconsistent with the hard X-ray data, particularly so if some fraction of the 10–100 keV X-rays is associated with a nuclear source contribution, as evidence for variability (Lea *et al.* 1981; Lea, Mushotzky, and Holt 1982) suggests. The *COS B* gamma-ray upper limit between 150 and 5000 MeV rules out values of $B^h{}_{\mu G} < 1.0$ due to overproduction of gamma rays from central region electrons Comptonizing the CMB. If our estimate for the CR proton intensity in M87 is valid, then the additional flux resulting from neutral pion decay gamma rays would violate the *COS B* upper limit unless $B^h{}_{\mu G} \gtrsim 1.5$.

Analysis of the *HEAO 1* hard X-ray data together with radio measurements has established a lower limit on the intracluster magnetic field of $\sim 1 \times 10^{-7}$ G in clusters with diffuse radio emission (Rephaeli, Gruber, and Rothschild 1987). Estimates for the equipartition magnetic field strength in the halo of M87 (neglecting proton energy density) give $B^h{}_{\mu G} \approx 4.0$ (Andernach *et al.* 1979) and $2 \lesssim B^h{}_{\mu G} \lesssim 5$ (Feigelson *et al.* 1987). Our calculation strengthens previous inverse Compton limits on the halo magnetic field (e.g., Lea *et al.* 1981) and shows that the mean halo magnetic field cannot be far below the equipartition value. Future gamma-ray observations are likely to strengthen these limits further (see below).

We also show in Figure 2 separate contributions from Comptonization of the optical and CMB fields by halo and central region electrons for the case $B^h{}_{\mu G} = 2.0$, as well as the flux expected from electron bremsstrahlung and neutral pion decay radiation in the central region. The behavior of the Comptonized fluxes at $\epsilon \gg 10$ MeV goes as $\epsilon^{-1.8}$, reflecting the dominance of Compton radiation by high-energy central region electrons in this regime. This also represents the behavior of the $\epsilon \gg 1$ GeV spectrum from pion production and decay. Near 200 MeV, however, a hardening of the model gamma-ray spectrum appears as the pion decay signature begins to dominate the total emission. Observation of such a hardening of the gamma-ray spectrum near this energy would provide strong evidence for the existence of CR protons in M87 but, as in our Galaxy, might be concealed by radiations associated with nonthermal electrons.

TABLE 1

PARAMETERS OF M87, PREDICTED >100 MeV GAMMA-RAY FLUX AND ESTIMATED OBSERVING TIME REQUIRED BY GRO EGRET TO IDENTIFY M87 AT 6 σ SIGNIFICANCE LEVEL[a]

			FLUX >100 MeV[b]			
$B^h(\mu G)$	$q_0(\times 10^{-46})/d^2_{20}$ (s^{-1})	τ(Myr)	Compton	π^0	Total	$t_{>100\,\mathrm{MeV}}$ $(10^6$ s)
1.5......	2.1	46.	1.2	0.88	2.3	0.35
2.0......	1.4	47.	0.70	0.60	1.4	0.94
3.0......	0.87	45.	0.33	0.36	0.76	3.2
5.0......	0.60	33.	0.12	0.18	0.34	16.

[a] Observing time required for detection at significance $N\sigma \propto N^2$.
[b] Units: 10^{-7} photons $cm^{-2}\,s^{-1}$.

Estimates of the integrated gamma-ray emissivity above 100 MeV are shown in Table 1 as a function of $B^h_{\mu G}$. The $B^h_{\mu G}$-dependence of the Compton flux $\propto B^{h\,-1.9}_{\mu G}$, whereas the dependence of the pion gamma-ray flux $\propto B^h_{\mu G}{}^{-1.3}$. Thus at larger values of the mean halo magnetic field, the pion contribution increasingly dominates the emission. The total >100 MeV flux for $B^h_{\mu G} = 1.5$ is a factor of $\sim$4 below the upper limit determined from *SAS 2* data, and the 150–5000 MeV flux for this value of $B^h_{\mu G}$ is below the *COS B* upper limit by a factor of $\sim$1–2. Enhanced sensitivity with the Egret gamma-ray telescope onboard GRO may permit identification of M87 at gamma-ray energies. Using the effective area of 1600 cm^2 for the Egret telescope and calculating the expected contributions from the diffuse galactic background (Fichtel, Simpson, and Thompson 1978) and extragalactic background (Thompson and Fichtel 1982) gamma-radiation, we have estimated the expected observing time required to identify M87 at the 6 σ level at $\epsilon > 100$ MeV, following Thompson (1986). These results are also listed in Table 1. Since only 45% of real time is available for observing a given source, a 6 σ detection M87 would require about 3.7 weeks if $B^h_{\mu G} = 2.0$. In spite of a larger photon flux from M87 at energies below 100 MeV, our estimates show that a 6 σ detection of M87 would require more observing time at lower energies because of the reduced sensitivity and angular resolution of Egret and the increased background flux. A 6 σ detection at $\epsilon \gg 100$ MeV could require a somewhat shorter observing time than required for a detection at 100 MeV, but these photons come increasingly from pion-associated processes, whose importance was estimated using an approximation (eq. [11]) which is less reliable than those based on the radio emission.

Observations of M87 with the Soviet-French gamma-ray experiment Gamma-1 (Akimov *et al.* 1985), although possessing a somewhat better angular resolution than GRO at $\epsilon = 100$ MeV, would require considerably more observing time because of its reduced sensitivity. The use of a coded aperture mask on Gamma-1 is probably better suited for identifying source positions of strong unidentified gamma-ray sources than searching for weak sources (Thompson 1986).

Our estimates show that M87 could be a considerably brighter gamma-ray source than M31 (Özel and Berkhuijsen 1987), in spite of the fact that M87 is $\sim$30 times farther away. This is because M87, a radio galaxy, has a radio luminosity $\sim 10^3$ times greater than spiral galaxies such as M31 or the Milky Way. Therefore the nonthermal electron spectra and resultant Comptonized fluxes are much more intense. But the estimates of the neutral pion-decay gamma radiation depend on the legitimacy of relating the proton and electron fluxes according to equation (11). This in turn depends on the supposition that there is a common mechanism for particle acceleration in M87 and the Milky Way. If, instead, the proton flux in M87 were at the same level as the CR flux measured in our Galaxy, M87 would be a very weak π^0 gamma-ray emitter. The mass of the diffuse gas within 90′ of M87 is $\sim 3 \times 10^{12}\, M_\odot$ (Fabricant and Gorenstein 1983), implying a gamma-ray emissivity of $\sim 1.0 \times 10^{-8}$ (photons >100 MeV) $cm^{-2}\,s^{-1}$, using 1.5×10^{-25} (photons >100 MeV) s^{-1} H $atom^{-1}$ for the π^0 gamma-ray emissivity from CR interactions in our Galaxy (e.g., Dermer 1986). Clearly M87 does not represent a useful source for examining the question of the universal nature of CR.

VI. SUMMARY

We have presented a model for the nonthermal electron spectra that describes the radio observations from the halo and central region of M87. We have used these observations to predict the gamma-ray emission from M87. *COS B* gamma-ray upper limits already restrict the value of the average halo magnetic field to be $\gtrsim 1.5\ \mu$G, representing an improvement of this limit over previous estimates of 0.5 μG (Lea *et al.* 1981) and 0.7–2.0 μG (Lea, Mushotzky, and Holt 1982), and is consistent with the value of $\sim$2.5 μG inferred from Faraday rotation studies (Dennison 1980*b*).

If indeed the mean halo magnetic field is near 2.5 μG, then our estimates imply that M87 should be identifiable at >100 MeV at the 6 σ significance level by the Egret telescope of GRO with an observing time $\sim$6–8 weeks. Observation of a hardening of the gamma-ray spectrum near 100 MeV would suggest a universal mechanism for cosmic-ray acceleration, as M87 is a giant elliptical radio galaxy unlike the Milky Way. Attempts to detect gamma-ray emission from M87 with Gamma-1 would probably require prohibitively long observing time.

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