ON SYNCHROTRON RADIATION FROM MESSIER 87

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ABSTRACT

The recent discovery by Baade that the optical radiation emitted by the jet in M87 is strongly polarized—and thus is synchrotron radiation—is a confirmation of a prediction made by Shklovsky and others. In this paper calculations of the required conditions of magnetic-field and particle energies are made, for both the optical and the radio emission. To account for the optical radiation in the jet, the total energy required in particles and field ranges from about 10^{54} to 10^{59} ergs for a series of assumed magnetic fields ranging from 10^{-2} to 10^{-6} gauss. To account for the radio emission for the same series of magnetic-field strengths, total energies in the range 10^{56}–10^{61} ergs are demanded. It is suggested that reasonable values are about 2×10^{55} ergs in particles and field, with $H \simeq 10^{-3}$ gauss, in the jet and about 10^{57} ergs in a volume 200 times greater than that of the jet, also with $H \simeq 10^{-3}$ gauss, which will explain the radio emission. By considering nuclear collisions of the high-energy protons with the static material present in the jet, it is shown that a continuous supply of electrons and positrons will be produced. If a density of about 3×10^{-22} gm/cc is assumed in the jet, the rate of electron-positron energy generation will be sufficient to balance the loss of energy by synchrotron radiation. The jet will also be a source of high-energy gamma radiation. Energy sources which might give rise to the primary particles and magnetic fields are discussed. It is suggested that the presence of antimatter in M87 would lead to a very powerful source of high-energy electrons and positrons.

I. INTRODUCTION

The observations by Baade (1956) of the polarization of the jet in M87 are convincing proof of the hypothesis that this optical radiation is synchrotron radiation emitted by relativistic electrons and positrons moving in magnetic fields in this region of the E0 galaxy. The prediction that this radiation might be polarized was made by Shklovsky (1955), who estimated some of the conditions necessary, and by Spitzer and Hoyle in unpublished discussions. In this paper we shall present some calculations leading to results which may be compared with the predictions of Shklovsky, and we shall discuss some of the implications of the results.

M87 is situated in the Virgo cluster, which has a mean red-shift velocity of 1136 km/sec (Humason, Mayall, and Sandage 1956). For a value of the Hubble constant of 180 km/sec/megaparsec (Humason *et al.* 1956) this gives a distance of 6.3×10^6 pc, which will be used for M87 in what follows. The dimensions of the jet are about 20″ by 2″, according to Baade and Minkowski (1954). Thus the linear dimensions are about 610×61 pc. The condensations in which Baade has detected about 30 per cent polarization lie near the end of the jet, which appears to extend all the way from the center of the galaxy (cf. the reproduction in the paper of Baade and Minkowski 1954), so that the effective large dimension may be less than 610 pc.

The absolute magnitude of the E0 galaxy is -19.2, so that it is one of the brightest of the known ellipticals. No accurate measures of the brightness of the jet are yet available. However, inspection of the plates suggests that it is comparable in brightness with the central region of M87 at a wave length near 4000 A. This central region probably has a luminosity near that of the center of M31, whose luminosity has been measured by Thiessen (1955). His curve shows that the luminosity is $+17$ mag/square second of arc. If we use this value for the jet, we find that its absolute magnitude is -16.0, if an area of 40 square seconds of arc is used. This value may be reduced if we suppose that only the condensations at the end of the jet with an area of 10 square seconds of arc are effective. Then $M = -14.5$. It is clear that in the photographic region the jet is not much fainter than this, and it may be brighter. To determine accurately the energy emitted corresponding to these luminosities, it would be necessary to know the form of the spectrum in this range. In view of the uncertainties, we shall neglect the differences in the photographic region between the jet spectrum, which may be a power-frequency spectrum of the form $P(\nu)d\nu = k\nu^{-x}d\nu$, and that of a black body. With these assumptions, the total power obtained in comparison with the sun in the photographic region is given by

$$\log \int_{\nu_1}^{\nu_2} P d\nu = 33.587 + 0.4\ (4.62 + 19.2 + m)\ ,$$

where $m = M(\text{M87}) - M(\text{jet}) = -3.2$ or -4.7. Thus the total power $= 6.8 \times 10^{41}$ or 1.7×10^{41} ergs/sec if $M(\text{jet}) = -16.0$ or -14.5. We shall suppose that this energy is emitted in a wave-length range $\lambda\lambda$ 4000–5500 corresponding to frequencies ν_2 and ν_1. We shall find it convenient to compute theoretically the power which will be radiated through the synchrotron mechanism at a frequency $\nu = 6.52 \times 10^{14}$ c/s ($\lambda = 4600$ A). Also a frequency-power spectrum of the form $P(\nu)d\nu = k\nu^{-x}d\nu$ will be assumed, where we shall put $x = 0.5$ and 1, respectively. For these two cases the equivalent band widths, $\Delta\nu$, such that

$$\int_{\nu_1}^{\nu_2} P d\nu = P_{(65.2\times 10^{14})} \Delta\nu$$

are 2.06×10^{14} and 2.08×10^{14}, respectively.

II. CALCULATION OF THE TOTAL ENERGY IN THE JET

The expressions for the power radiated and the critical frequency of radiation in the synchrotron mechanism have been given by Schwinger (1949) and others, and integrals similar to those needed here have already been used by Oort and Walraven (1956) in their analysis of the Crab Nebula. Thus only a brief treatment will be given here, since our discussion necessarily follows theirs quite closely.

The power radiated by an electron or positron of energy E per c/s moving in a magnetic field of strength H is given by

$$p\ (\nu) = 2.343 \times 10^{-22} H \sin\ \theta \frac{\nu}{\nu_c} \int_{\nu/\nu_c}^{\infty} K_{5/3}\ (\eta)\ d\eta\ , \tag{1}$$

where θ is the angle between the velocity vector and H. The critical frequency, ν_c, is given by

$$\nu_c = 6.269 \times 10^{18} H \sin\theta\, E^2 = 4.19 \times 10^6 H \sin\theta\ \gamma^2\ , \tag{2}$$

where $\gamma = E/mc^2$. The radiation is totally polarized, with the electric vector parallel to the radius of curvature of the orbit, and it is emitted in a very sharp cone, with its axis the velocity vector and an angle of mc^2/E.

We shall suppose that the differential energy-spectrum of the electrons which give rise to the radiation is of the form

$$N\ (E)\ dE = K E^{-n} dE\ , \tag{3}$$

and we shall put $n = 2$ or 3.

If we define $\phi(\nu_c)$ as the number of electrons with critical frequency ν_c in a unit frequency interval about ν_c, then

$$\phi(\nu_c)\, d\nu_c = KE^{-n} dE ; \tag{4}$$

and, using equation (2), we find

$$\phi(\nu_c) = \frac{K}{2} \nu_c^{-(n+1)/2} (kH_e)^{\frac{n-1}{2}}, \tag{5}$$

where $k = 6.269 \times 10^{18}$ and $H_e = H\langle \sin\theta \rangle_{\text{av}} = H\pi/4$. The intensity of radiation at a particular frequency is

$$J(\nu) = \int_0^\infty P(\nu)\, \phi(\nu_c)\, d\nu_c . \tag{6}$$

If we now write

$$F(\alpha) = \alpha \int_0^\infty K_{5/3}(\eta)\, d\eta , \tag{7}$$

where

$$\alpha = \frac{\nu}{\nu_c},$$

TABLE 1

ELECTRON ENERGIES NECESSARY TO PRODUCE RADIATION IN OPTICAL RANGE

H (gauss)	$E_c(\lambda=4000$ A) (ev)	$E_c(\lambda=5500$ A) (ev)	$E(\lambda=4600$ A) (ev)	
			$\alpha=10$	$\alpha=0.01$
10^{-2}	$6\ 84\times10^{10}$	$5\ 84\times10^{10}$	$2\ 02\times10^{10}$	$6\ 37\times10^{11}$
10^{-3}	$2\ 16\times10^{11}$	$1\ 84\times10^{11}$	$6\ 37\times10^{10}$	$2\ 02\times10^{12}$
10^{-4}	$6\ 84\times10^{11}$	$5\ 84\times10^{11}$	$2\ 02\times10^{11}$	$6\ 37\times10^{12}$
10^{-5}	$2\ 16\times10^{12}$	$1\ 84\times10^{12}$	$6\ 37\times10^{11}$	$2\ 02\times10^{13}$
10^{-6}	$6\ 84\times10^{12}$	$5\ 84\times10^{12}$	$2\ 02\times10^{12}$	$6\ 37\times10^{13}$

and substitute from equations (1), (5), and (7) in equation (6), we find

$$J(\nu) = 1.1711 \times 10^{-22} K \left(\frac{\nu}{kH_e}\right)^{(1-n)/2} \int_0^\infty F(\alpha)\, \alpha^{(n-3)/2} d\alpha . \tag{8}$$

The function $F(\alpha)$ for $0.001 < \alpha < 10.67$ has been tabulated by Oort and Walraven, and they have pointed out that the following approximations can also be made:

$$\alpha < 0.01 , \quad F(\alpha) \simeq 2.15\alpha^{1/3} ;$$

$$\alpha > 10 , \quad F(\alpha) \simeq 1.26\alpha^{1/2} \exp(-\alpha) . \tag{9}$$

The electron energies which are demanded in order that ν_c may lie in the optical range have been computed from equation (2) for values of H_e ranging from 10^{-2} to 10^{-6} gauss. The energy limits outside which electrons will no longer contribute appreciably to the power emitted in the photographic range have been delineated by computing values of E_c from equation (2) for $\alpha = 10$ and $\alpha = 0.01$, where $\nu = 6.52 \times 10^{14}$ c/s. All these values are given in Table 1.

The integral in equation (8) has been evaluated by numerical integration for $n = 2$ and 3. Hence $J(\nu)$ has been determined for $\nu = 6.52 \times 10^{14}$ c/s. Now we have, from our previous estimate of the total power radiated,

$$J\,(\nu = 6.52 \times 10^{14}) = y \times 10^{41} \times (\Delta\nu)^{-1}\,, \tag{10}$$

where $y = 6.8$ or 1.7; $\Delta\nu = 2.06 \times 10^{14}$ for $n = 2$; and $\Delta\nu = 2.08 \times 10^{14}$ for $n = 3$. By substituting equation (10) in equation (8), we have determined K. We find that

$$\begin{aligned} &\text{If } n = 2\,, \qquad K = y H_e^{-3/2} \times 1.999 \times 10^{45}\,; \\ &\text{If } n = 3\,, \qquad K = y H_e^{-2} \times 2.689 \times 10^{43}\,. \end{aligned} \tag{11}$$

Now the total energy in the electrons is as follows:

$$\begin{aligned} \epsilon &= K \int_{E_1}^{E_2} \frac{dE}{E^{n-1}} \\ &= K \left(\frac{1}{E_1} - \frac{1}{E_2} \right) \qquad \text{when } n = 3\,, \\ &= K \log \left(\frac{E_2}{E_1} \right) \qquad \text{when } n = 2\,. \end{aligned} \tag{12}$$

TABLE 2

TOTAL PARTICLE AND MAGNETIC ENERGIES IN THE JET

H (gauss)	$\epsilon/y (n=3)$ (ergs)	$\epsilon/y (n=2)$ (ergs)	$(\epsilon/y)(M/m)$ $(n=3)$ (ergs)	$\mathfrak{M}$ (ergs)	Particle Energy Density $(\epsilon/y)(M/m)(1/\pi r^2 d)$ (ev/cc)
10^{-2}	$8\ 3 \times 10^{49}$	$6\ 9 \times 10^{49}$	$1\ 5 \times 10^{53}$	$2\ 1 \times 10^{56}$	$1\ 8 \times 10^{3}$
10^{-3}	$2\ 6 \times 10^{51}$	$2\ 2 \times 10^{51}$	$4\ 8 \times 10^{54}$	$2\ 1 \times 10^{54}$	$5\ 7 \times 10^{4}$
10^{-4}	$8\ 3 \times 10^{52}$	$6\ 9 \times 10^{52}$	$1\ 5 \times 10^{56}$	$2\ 1 \times 10^{52}$	$1\ 8 \times 10^{6}$
10^{-5}	$2\ 6 \times 10^{54}$	$2\ 2 \times 10^{54}$	$4\ 8 \times 10^{57}$	$2\ 1 \times 10^{50}$	$5\ 7 \times 10^{7}$
10^{-6}	$8\ 3 \times 10^{55}$	$6\ 9 \times 10^{55}$	$1\ 5 \times 10^{59}$	$2\ 1 \times 10^{48}$	$1\ 8 \times 10^{8}$

We have put $E_1 = E_c$ when $\alpha = 10$ and $E_2 = E_c$ when $\alpha = 0.01$. From equations (11) and (12) we have computed ϵ/y for values of H_e ranging from 10^{-2} to 10^{-6} gauss. These values are shown in Table 2. Also included in this table are values of the total magnetic energy, $\mathfrak{M}$, which has been computed on the assumption that the jet has a cylindrical form with $l = 610$ pc and $r = 30.5$ pc, so that $\mathfrak{M} = H_e^2 r^2 l/8$. Most considerations regarding the origin of the particles in the jet lead us to believe that, besides the electrons and positrons, a large density of protons must also be present. Thus we have also included in Table 2 values of the total particle energy and energy density calculated on the assumptions that the protons have energies M/m times those of the electrons and that the numbers of protons and electrons are equal. This might be the case if they were both primary components accelerated together but would certainly not be true if the electrons and positrons arose as secondary particles. These points will be discussed more fully in Sections VI and VII. Before discussing the implications of these results, it is of some interest to consider the origin of the radio energy emitted by M87.

III. RADIO POWER EMITTED BY M87

M87 is well known as a strong radio source. However, there is no evidence that the radio source is localized on the jet. The source has been generally believed to have an angular diameter of about 5′ (Pawsey 1955), corresponding to a dimension of 9180 pc, and to be roughly coincident with the optical E0 galaxy. Measurements of the power received at 18.3, 60, 81.5, 100, 101, and 3200 Mc/s have been listed by Pawsey. These enable us to make an estimate of the form of the power-frequency spectrum. If this is written in the form $P(\nu) = k\nu^{-x}$, it is found that a unique value of x cannot be assigned to cover the whole of the observed range of frequencies. This is characteristic of other extragalactic sources (cf. Burbidge 1956). The two curves which give a reasonable fit are

$$P(\nu) = 3.23 \times 10^{11}\nu^{-1\ 3}, \qquad 1.83 \times 10^{7} < \nu < 2 \times 10^{8}$$

and

$$P(\nu) = 5.00 \times 10^{5}\nu^{-0\ 6}, \qquad 2 \times 10^{8} < \nu < 3.2 \times 10^{9}.$$

Here $P(\nu)$ is measured in units of 10^{-24} watt/m²/c/s. Also $\nu = 2 \times 10^{8}$ has been chosen as a convenient point at which to join the slopes of two roughly determined curves. It has no other significance. We have now obtained the total power radiated in the radio spectrum by integrating these two curves between two *assumed* cutoffs, $\nu_1 = 10^7$ c/s and $\nu_3 = 3.5 \times 10^9$ c/s. This integration gives a total power output from the radio source of 5.1×10^{40} ergs/sec.

IV. CALCULATION OF TOTAL ENERGY NECESSARY TO PRODUCE RADIO POWER

To determine the total energy in the electrons necessary to produce the radio power, we proceed in a slightly different way from that used in Section II. The total energy emitted per second by an electron of energy E is given by

$$-\frac{dE}{dt} = 2\ 368 \times 10^{-3} H_e^2 E^2 = 1.58 \times 10^{-15} H_e^2 \gamma^2. \qquad (13)$$

Thus, if the electron-energy spectrum is of the form

$$N(E)\, dE = K_1 E^{-m} dE, \qquad (14)$$

the total energy emitted by the electrons per second is

$$5.1 \times 10^{40} = 2.368 \times 10^{-3} H_e^2 K_1 \int_{E_1}^{E_3} E^{-m+2} dE. \qquad (15)$$

Now the total energy in the electrons, ϵ, is given by

$$\epsilon = K_1 \int_{E_1}^{E_3} E^{-m+1} dE, \qquad (16)$$

where E_1, E_2, and E_3 have been determined from equation (2) by putting $\nu_1 = 10^7$, $\nu_2 = 2 \times 10^8$, and $\nu_3 = 3.5 \times 10^9$. These values are given in Table 3. The electron spectrum has been written in the form

$$N(E)\, dE = K_1 E^{-m_1} \qquad (E_1 < E < E_2),$$

$$N(E)\, dE = K_1 E_2^{(-m_1+m_2)} E^{-m_2} \qquad (E_2 < E < E_3).$$

By eliminating K_1 between equations (15) and (16), we find that

$$\epsilon = 2.154 \times 10^{43} H_e^{-2} \times [(m_1 - 2)^{-1} (E_1^{2-m_1} - E_2^{2-m_1}) + E_2^{(-m_1+m_2)} (m_2 - 2)^{-1} (E_2^{2-m_2} - E_3^{2-m_2})] \times [(m_1 - 3)^{-1} (E_1^{3-m_1} - E_2^{3-m_1}) + E_2^{(-m_1+m_2)} (m_2 - 3)^{-1} (E_2^{3-m_2} - E_3^{3-m_2})]^{-1} . \quad (17)$$

Since it is easily shown that the relation between the indices in the electron spectrum and in the power-frequency spectrum is $m = (2x + 1)$, we have put $m_1 = 3.6$ and $m_2 = 2.2$. The right-hand side of equation (17) has then been evaluated for H_e ranging from 10^{-2} to 10^{-6} gauss. These values are shown in Table 4. Also included in this table

TABLE 3

ELECTRON ENERGIES NECESSARY TO PRODUCE RADIATION IN THE RADIO-FREQUENCY RANGE

H (gauss)	E_1 (ev)	E_2 (ev)	E_3 (ev)	H (gauss)	E_1 (ev)	E_2 (ev)	E_3 (ev)
10^{-2}	$7\ 9\times10^{6}$	$3\ 5\times10^{7}$	$1\ 5\times10^{8}$	10^{-5}	$2\ 5\times10^{8}$	$1\ 1\times10^{9}$	$4\ 7\times10^{9}$
10^{-3}	$2\ 5\times10^{7}$	$1\ 1\times10^{8}$	$4\ 7\times10^{8}$	10^{-6}	$7\ 9\times10^{8}$	$3\ 5\times10^{9}$	$1\ 5\times10^{10}$
10^{-4}	$7\ 9\times10^{7}$	$3\ 5\times10^{8}$	$1\ 5\times10^{9}$				

TABLE 4

TOTAL PARTICLE AND MAGNETIC ENERGIES TO PRODUCE THE RADIO EMISSION

H (gauss)	ϵ (ergs)	$(M/m)\epsilon$ (ergs)	$\mathfrak{M}$ (ergs)	$(M/m)(3\epsilon/4\pi r^3)$ (ev/cc)
10^{-2}	$5\ 6\times10^{51}$	$1\ 0\times10^{55}$	$4\ 7\times10^{61}$	$5\ 4\times10^{-1}$
10^{-3}	$1\ 8\times10^{53}$	$3\ 2\times10^{56}$	$4\ 7\times10^{59}$	$1\ 7\times10$
10^{-4}	$5\ 6\times10^{54}$	$1\ 0\times10^{58}$	$4\ 7\times10^{57}$	$5\ 4\times10^{2}$
10^{-5}	$1\ 8\times10^{56}$	$3\ 2\times10^{59}$	$4\ 7\times10^{55}$	$1\ 7\times10^{4}$
10^{-6}	$5\ 6\times10^{57}$	$1\ 0\times10^{61}$	$4\ 7\times10^{53}$	$5\ 4\times10^{5}$

are estimates of the total magnetic energy, $\mathfrak{M}$, computed on the assumption that the radio emission arises in a sphere of radius $r = 4590$ pc, so that $\mathfrak{M} = H_e^2 r^3/6$. We have also included in Table 4 total particle energies and energy densities computed by supposing that the protons have M/m times the energy of the electrons and that the numbers of protons and electrons are equal. Equation (17) has been used to calculate the total energy of the electrons in preference to one similar to equation (8), because the range of frequencies involved is such that $\nu_3/\nu_1 \gg 1$. In this case the slight inaccuracy present is due to the fact that we are neglecting electrons lower than E_1 and greater than E_3, which may contribute a small amount to the radio emission. On the other hand, we are also neglecting the radiation emitted slightly outside our chosen cutoffs by the electrons of energies E_1 and E_3. It is clear that ϵ is roughly proportional to the value of E_1^{-1}, so that this value is important in defining the minimum energy that the electrons can have. A conservative estimate has been made by putting $\nu_1 = 10^7$ c/s, since this is quite close to the lowest frequency 1.83×10^7 c/s for which measurements are available.

V. COMPARISON OF THE OPTICAL WITH THE RADIO SPECTRUM

It is of some interest to consider briefly whether the form of the frequency-power spectrum is compatible with the idea that both the optical and the radio emission arise from a unique electron spectrum, over most of the frequency range 10^7–10^{15} c/s. It has already been pointed out that the radio spectrum does not appear to be unique. However, the frequency-power spectrum $P(\nu) = 5.00 \times 10^5 \nu^{-0\,6}$ for $2 \times 10^8 \leq \nu \leq 3.5 \times 10^9$ is rather uncertain, since the value 0.6 depends rather critically on one (low) value of the power measured at 32×10^9 c/s. Thus, for the time being, we shall ignore this relation and write

$$P\,(\nu) = k\nu^{-x} \qquad (\nu_1 < \nu < \nu_2)$$

and determine x for (*a*) $\nu_1 = 10^8$, $\nu_2 = 6.52 \times 10^{14}$, and (*b*) $\nu_1 = 3.2 \times 10^9$, $\nu_2 = 6.52 \times 10^{14}$. We have no observational knowledge concerning the spectrum within the optical range (previous dependences have been *assumed*), so we shall put $P(\nu = 6.52 \times 10^{14}) = 10^{41} \times y/(2.04 \times 10^{+14}) = 4.902 \times 10^{26} \times y$. With these assumptions, we find, for case a, $x = 0\,62$ and 0.71 for $y = 6.8$ and 1.7; for case b, $x = 0.62$ and 0.73 for $y = 6.8$ and 1.7. Thus, despite all the uncertainties connected with the various aspects of the problem, it appears that an index between 0.6 and 0.7 would be sufficient to represent all the observations between $\nu = 10^{15}$ and 10^8 c/s, while an index of 1.3 would represent the observations between $\nu = 10^8$ and 10^7 c/s. Thus a unique electron spectrum with an index of -2.2 is indicated over most of the energy range. However, this index becomes more negative, reaching a value of -3.6 at the low-energy end. The energy ranges over which these indices are appropriate cannot be determined unless assumptions are made about the effective magnetic fields. These will be discussed in Section VII.

VI. NUCLEAR COLLISIONS IN THE JET

In Tables 2 and 4 we have tabulated the total energy in the particles on the assumption that the proton energy is M/m times that of the electrons and that protons and electrons are present in equal numbers. If both protons and electrons are of primary origin and if they have both been accelerated in the turbulent gas in the jet by induction-type mechanisms, of which the Fermi mechanism and the Swann betatron mechanism are examples, this procedure would be correct in the idealized case. However, it is well known that electrons are more difficult to accelerate by these mechanisms, because of their large energy losses in the low-energy region by bremsstrahlung and collisional ionization processes. Thus other mechanisms of electron and positron production must be considered. One of the most obvious assumptions is to suppose that they are of secondary origin and are produced as the end-products following nuclear collisions between high-energy primary protons and the nuclei at the kinetic temperature of the jet.

We shall suppose that the number-density of the material at kinetic temperature in the jet is n/cc. Now the lifetime for a high-energy proton between nuclear collisions in the jet is given by

$$\tau = \frac{1}{\sigma_A n_A c}, \tag{18}$$

where σ_A is the appropriate cross-section for collision. For proton-proton collisions we shall put $\sigma = 4 \times 10^{-26}$ cm^2, while for elements of atomic weight A, $\sigma_A = \pi r^2 A^{2/3}$, where $r = 1.4 \times 10^{-13}$ cm (this value of r may be an overestimate for very high-energy collisions). Thus, for p-p collisions,

$$\tau = \frac{8.33 \times 10^{14}}{n}, \tag{19}$$

and, for p–heavy-particle collisions,

$$\tau_A = \frac{5.41 \times 10^{14}}{n_A A^{2/3}}. \tag{20}$$

If we assume that normal cosmic abundances were present originally in the jet, it is clear that, except for $A = 4$, $n \gg n_A A^{2/3}$. Thus, although the total multiplicity of electrons and positrons may be greater for collisions involving heavy particles, in this approximation we can neglect their influence. However, equation (20) will be used when we discuss spallation. We shall suppose that the total proton energy is Y ergs, and, to simplify the discussion, no specific proton-energy spectrum will be assumed, but we shall put

$$Y = N\langle E\rangle , \tag{21}$$

where $\langle E\rangle$ is the mean energy of the primary protons such that the secondary electrons lie in the range to produce optical radiation. In a collision between two protons with total kinetic energy $\langle E\rangle \gg Mc^2$ the following particles and their decay products will be produced:

(*a*) $\pi^{\mp} \rightarrow \mu^{\mp} + \nu \rightarrow e^{\mp} + 3\nu ,$

$\pi^0 \rightarrow 2\gamma ;$

(*b*) $\tau^{\mp} \rightarrow 2\pi^{\pm} + \pi^{\mp} \rightarrow 2\mu^{\pm} + \mu^{\mp} + 3\nu \rightarrow 2e^{\pm} + e^{\mp} + 9\nu ,$

$\theta^0 \rightarrow \pi^+ + \pi^- \rightarrow \mu^+ + \mu^- + 2\nu \rightarrow e^+ + e^- + 6\nu ;$

(*c*) $p, \bar{p},$

$n \rightarrow p + e^- + \nu ,$

$\bar{n} \rightarrow \bar{p} + e^+ + \nu ;$

(*d*) $\Lambda^0 \rightarrow p + \pi^- \rightarrow p + \mu^- + \nu \rightarrow p + e^- + 3\nu ,$

$\Sigma^+ \rightarrow p + \pi^0 \rightarrow p + 2\gamma ,$

$\Sigma^{\pm} \rightarrow n + \pi^{\pm} \rightarrow p + e^- + \mu^{\pm} + 2\nu \rightarrow p + e^- + e^{\pm} + 6\nu ,$

$\Xi^- \rightarrow \Lambda^0 + \pi^- \rightarrow p + 2\mu^- + 2\nu \rightarrow p + 2e^- + 6\nu .$

Some of the hyperon-decay schemes listed under category d are still uncertain. The multiplicity of electrons can be estimated from the statistical theory of Fermi (1950). Although it is not in especially good agreement with experiment at energies not too far above the threshold, it should be a better approximation in the very high-energy region which we are considering here. Fermi considered only the production of π mesons and nucleons and antinucleons, since the particles in categories b and d had not yet been discovered. He showed that the multiplicities of π mesons, s_1, and of nucleons and antinucleons, s_2, were given by

$$s_1 = 0.54\sqrt{W}$$

and

$$s_2 = 1.30\sqrt{W} , \tag{22}$$

where

$$W = \sqrt{\frac{2\langle E\rangle}{Mc^2}} .$$

The greater number of nucleons and antinucleons is due to their greater statistical weight. Since the K mesons (τ, θ) have masses intermediate between π mesons and nucleons, they will have a lower threshold for production than nucleons and antinucleons. Their statistical weights are uncertain, but their presence will mean that their multiplicity will be increased at the expense of the other particles. The effect of the presence of hyperons is difficult to estimate and will be neglected.

We shall suppose that the total multiplicity of particles is still equal to $1.84\sqrt{W}$ but that the relative statistical weight of the K mesons relative to the nucleons and antinucleons is $\frac{3}{8}$. Then, from the decay schemes given here, we estimate that the total electron multiplicity, s_3, is given by

$$s_3 = 1.78\sqrt{W}\,, \tag{23}$$

and the total electron energy after a collision, E_t, is

$$E_t = \frac{0.16}{1.84}\langle E\rangle\,. \tag{24}$$

Thus the average electron energy, E_e, is given by

$$E_e = \frac{\langle E\rangle}{\sqrt{W}}\times 0.049\,. \tag{25}$$

TABLE 5

PRIMARY PROTON ENERGIES AND ELECTRON MULTIPLICITIES NECESSARY TO PRODUCE ELECTRONS WHICH WILL EMIT IN THE OPTICAL RANGE

H (gauss)	$E_e(\lambda=4000$ A) (ev)	$\langle E\rangle$ (ev)	s_3	Mean γ-Ray Energy (ev)
10^{-2}	$6\ 84\times10^{10}$	$3\ 1\times10^{13}$	16	$5\ 3\times10^{11}$
10^{-3}	$2\ 16\times10^{11}$	$1\ 5\times10^{14}$	23	$1\ 7\times10^{12}$
10^{-4}	$6\ 84\times10^{11}$	$6\ 8\times10^{14}$	34	$5\ 3\times10^{12}$
10^{-5}	$2\ 16\times10^{12}$	$3\ 1\times10^{15}$	50	$1\ 7\times10^{13}$
10^{-6}	$6\ 84\times10^{12}$	$1\ 5\times10^{16}$	74	$5\ 3\times10^{13}$

Here we have assumed that the total energy available is divided equally among all the particles produced and then equally among all their decay products. Values of E_e taken from Table 1 (corresponding to the production of optical radiation at λ 4000 A) have been used to calculate from equations (23) and (25) the electron multiplicities and energies of primary protons. These values are shown in Table 5.

With the assumptions we have made, the total energy available in a collision will be carried away in the following proportions: neutrinos, $\simeq$45 per cent; protons and antiprotons, $\simeq$35 per cent; electrons, $\simeq$10 per cent; and gamma radiation, $\simeq$10 per cent. It might be thought that the γ radiation emitted in the decay of the π^0 mesons would produce electron-positron pairs in the jet. However, the mean free path for γ radiation against pair production is about $6\times10^{25}/n$ cm, so that, unless $n\geq10^4$, the major proportion of the γ rays will escape from the jet without producing pairs. Thus, if our assumptions are correct, the jet should be a source of γ rays emitting at a power level which is approximately equal to the rate of electron-energy production. It would be interesting to see whether the gamma radiation from M87 could be detected by the cosmic-ray workers. Our calculations suggest that the intensity of gamma radiation to be expected would be 10^{-9}–10^{-11}/cm^2/sec at the top of the atmosphere. Average energies of the γ rays have been estimated and are given in Table 5.

From equations (19) and (21) we find that the total number of collisions taking place per second is given by

$$\frac{Yn}{\langle E\rangle \times 8.33\times 10^{14}},$$

and, from equation (24), the total energy in electrons produced per second is given by

$$Yn\times 1.044\times 10^{-16}\,.$$

Now, if there is to be no energy loss or gain,

$$y\times 10^{41} = Yn\times 1.044\times 10^{-16}$$

or

$$Y=\frac{9.58\times 10^{56}y}{n}, \tag{26}$$

where y = 6.8 or 1.7. Values of Y for a number of assumed values for n and the corresponding total mass of the jet are shown in Table 6. It is clear that the secondary produc-

TABLE 6

ESTIMATED PROTON FLUX ENERGIES IF ELECTRONS AND PROTONS ARE PRODUCED IN NUCLEAR COLLISIONS

n	$Y(y=6.8)$ (ergs)	$Y(y=1.7)$ (ergs)	Mass of Jet (gm)	n	$Y(y=6\ 8)$ (ergs)	$Y(y=1.7)$ (ergs)	Mass of Jet (gm)
1 .	6 5×10^{57}	1 6×10^{57}	8 7×10^{37}	10^2	6 5×10^{55}	1 6×10^{55}	8 7×10^{39}
10 . .	6 5×10^{56}	1 6×10^{56}	8 7×10^{38}	10^3	6 5×10^{54}	1 6×10^{54}	8 7×10^{40}

tion of electrons is an important effect, whether or not primary high-energy electrons were originally present.[1] The characteristic time scale, t_1, for the optical emission is of the order of $Y\times 10^{-41}$ seconds.

The other important time scale, t_2, is that for the electrons and positrons to lose an appreciable fraction of their energy by synchrotron emission. If there is no source of energy gain after the electrons and positrons have been produced, this time (t_2) will be given by the integral of equation (13). However, it is probable that, apart from the high-energy particles, the majority of the material in the jet will be in a state of hydromagnetic turbulence and that its turbulent energy will be roughly in equipartition with the magnetic energy. In this case we shall have

$$v^2=\frac{3H^2}{8\pi\rho}=\frac{H^2}{n}\,7.16\times 10^{22}\,.$$

The electrons and positrons will therefore gain energy in Fermi collisions with the turbulent clouds, and this rate of gain is given approximately by

$$\frac{\delta E}{\delta t}=E\left(\frac{v}{c}\right)^2\frac{c}{l}, \tag{27}$$

[1] It is probable that the effect of nuclear collisions in the Crab Nebula will be important. This question will be considered elsewhere.

where l is the distance traveled between successive collisions. Thus, using equations (13) and (27) and substituting for v^2, we find that the net loss of energy is given by

$$-\frac{dE}{dt}=1.58\times 10^{-15}H^2\left(\frac{E}{mc^2}\right)^2-\frac{EH^2}{nl}\times 7.16\times 10^{22}\ \text{ergs/sec}\,.$$

If there is to be no energy loss,

$$l\leq 1.51\times 10^{27}\frac{E}{n}\left(\frac{mc^2}{E}\right)^2. \tag{28}$$

Now, if we anticipate our concluding discussion and suppose that the total energies of the particles and the field are the minimum values obtained by interpolating in Table 2, we have $H = 10^{-3}$ gauss and $E = 2\times 10^{11}$ ev. Thus, for $n = 10^2$ for no energy loss,

$$l\leq 3\times 10^{13}\ \text{cm}\,.$$

This value is extremely small and does imply that the turbulence in the jet has extremely fine structure. On the other hand, if we suppose that $l > 3\times 10^{13}$ cm, then the time scale for the buildup process through nuclear collisions is governed by the fact that it must be less than t_2, which, for the values of E and H taken above, is of the order of 100 years. As well as implying that the jet is a very short-lived phenomenon, this also demands that the total energies involved in particles and field are greater than those obtained by interpolating in Table 2.[2] An estimate of the proton energy required can be made by supposing that the electron flux is built up in about 100 years. In this case we have

$$Y = 3.04\times 10^6\left(\frac{\epsilon}{n}\right),$$

and, if $H = 10^{-2}$ and 10^{-3} gauss, $n = 10^2$, $Y \simeq 2\times 10^{56}$ and 7×10^{57} ergs, respectively. It is clear that if H were 10^{-3} gauss, the majority of the protons would rapidly escape from the jet. On the other hand, if the field were about 10^{-2} gauss, the total magnetic and particle energies would be approximately equal.

It remains to discuss briefly the possible spallation effects which may take place in the jet. These will continuously increase the relative abundances of the light elements at the expense of the heavier ones. One of the most interesting of the effects is the gradual building up of the lithium, beryllium, and boron group, which is extremely rare in the normal abundance-curve. The cosmic-ray work (Kaplon, Noon, and Racette 1954, and other references) suggests that in a spallation collision between a fast proton and a slow (thermal) carbon, nitrogen, or oxygen nucleus there is a large probability that a lithium, beryllium, or boron nucleus will be emitted. Thus from equations (20) and (21), putting $A = 16$, and $n(\text{C, N, O}) = 10^{-3}\,n$, we find that the approximate rate of production of lithium, beryllium, and boron is

$$\frac{dn}{dt}(\text{Li, Be, B}) = 2.15\times 10^{-22}\langle E\rangle^{-1}/\text{cc}\,.$$

Since the minimum value of $\langle E\rangle$ is about 10 ergs (Table 5), it is clear that the rate of buildup relative to the "static" material is negligible. The fragments which are produced will, in general, have energies much lower than those of the colliding protons but much higher than those of the "static" material. The density of the fast particles is only

[2] If fine-structured turbulence were present, it is probable that the protons as well as the electrons would gain energy from the gas by a modified Fermi process. This would not be so efficient as the electron acceleration process, since, for protons having energies greater than 10^{13}–10^{14} ev, the radii of the proton orbits would be comparable with, or greater than, the value of l suggested here.

$(Y/\langle E\rangle \times 1.9 \times 10^{-62}$ cc, and if the carbon, nitrogen, and oxygen comprised 10^{-3} of this density, then the lithium, beryllium, and boron group would attain equilibrium with it in a time $t = 9 \times 10^{-42}\ Y$ seconds, i.e., a time comparable with the time scale for optical radiation. Deuterium will also be produced, but sufficient experimental evidence is not available to estimate its rate of production.

VII. DISCUSSION

The most remarkable result of the computations described in this paper is the tremendous amount of energy contained in the magnetic field and the charged particles which is necessary to explain both the optical radiation from the jet and the radio emission. The numbers which we have derived here can be compared with the total energy in cosmic radiation and magnetic field in our own Galaxy, which we estimate (assuming an energy density of about 1 ev/cc in the particles and a magnetic field $\sim 10^{-5}$ gauss) to be about 10^{54} ergs. As far as they can be compared, our results are in good agreement with the estimates of Shklovsky, who used a magnetic field of the order of 10^{-4} gauss and then estimated that the total particle energy should be about 10^{56}–10^{57} ergs.

If we suppose that in the jet there is rough equipartition between the magnetic and kinetic energy modes, then we can interpolate in Table 2 to obtain the total energy of the system. The result is that the total energy is about 2×10^{55} ergs, and the mean magnetic field is about 1×10^{-3} gauss. However, this is a minimum value of the energy, and the difficulties associated with the production of electrons and positrons if these values are assumed are discussed in Section VI. It may be that a larger value of the total energy of about 4×10^{56} ergs and a mean magnetic field of about 10^{-2} gauss are more reasonable. If a mean density of about 200/cc corresponding to a total mass of the jet of about 10^{-4} times that of the whole galaxy is assumed, the system may be in equilibrium for short time scales as far as the optical radiation is concerned. This condition depends both on the efficiency of Fermi collision processes and on the total proton energy. The equipartition condition between magnetic and turbulent kinetic energy demands that, for assumed values of H of 10^{-3} or 10^{-2} gauss, the turbulent velocities will be 150 or 1500 km/sec.

As far as the radio emission is concerned, two extreme possibilities can be considered: (i) We can suppose that the radio source is located in the jet alone, in which case, if we use the value of the magnetic field determined from the equipartition argument for the optical radiation, the total particle energy is about 5×10^{56} ergs; (ii) or we can suppose that the area of radio emission is spread over the whole volume, corresponding to an angular diameter of about $5'$. In this case the minimum total energy demanded by the equipartition argument would be about 10^{58} ergs, with an effective magnetic field of about 10^{-4} gauss. It is possible that the radio emission arises in a volume greater than that of the jet but less than that of the whole galaxy. For example, if the volume were about two hundred times greater than that of the jet, the total energy would be about 10^{57} ergs equally divided between a magnetic field of about 10^{-3} gauss and the high-energy particles. It has been shown elsewhere (Burbidge and Burbidge 1956) that in the radio sources NGC 5128 and NGC 1316, which do not show non-thermal optical emission, energy sources of the same orders of magnitude must be present.

The origin of the particles giving rise to the radio emission is uncertain. Shklovsky has made the interesting suggestion that they have been degraded in energy in radiating in the jet and have then diffused outward. A second possibility is that they are also secondary and are being continuously produced in nucleon-nucleon collisions in a lower-energy range, though here the multiplicities are lower than those estimated for the jet and also the rate of interaction is much lower because of the smaller density of static material which must reasonably be inferred.

Equipartition of energy between magnetic field and material motion need not always be assumed in systems of this kind. The balance will depend on the age of the system and the original energy source. It is clear that this type of indirect observation of great amounts of non-thermal energy may lead to revision of current ideas concerning the possible magnetic-field strengths, for example, in an early epoch of galactic formation. It may be that large fields—very much greater than those indicated by theoretical stability arguments and by indirect observational methods in our Galaxy ($\simeq 10^{-5}$ gauss)—are initially built in the very early stages of galactic evolution and that these later decay by hydromagnetic means, thus providing a source of turbulent kinetic energy. The role of stars in these processes is not understood. However, the large amounts of energy which Oort and Walraven have shown to be present in particles and field in the Crab Nebula are comparable on a stellar scale to those discussed here on a galactic scale, and in the case of the Crab Nebula the energy source may be connected with the "moving ripples" observed by Baade near the central star with velocities of the order of $c/5$.

It is clear that, in order to investigate this phenomenon more fully, extensive observing programs should be undertaken in an attempt to detect more objects showing the large degree of polarization characteristic of the synchrotron radiation. Thus, in addition to optical studies of known radio sources, if a strong non-stellar continuum is present, it would be worthwhile to investigate other galaxies which may not be detectable radio sources but which are chosen after preliminary study of their optical spectra. Since the synchrotron radiation may reach a maximum in any region of frequency, depending on the cutoffs and on the conditions of magnetic field and particle acceleration, all accessible regions of the spectrum, including, for example, the infrared, demand investigation.

Very few of the potential sources of energy which we know of in nature are comparable in magnitude to those present here. The kinetic energy of two galaxies in interaction with a relative velocity of about 1000 km/sec is about 10^{60} ergs, and the potential energy of a galactic mass is about 10^{59} ergs. The total amount of energy emitted in a supernova outburst is estimated to be 10^{49}–10^{50} ergs. Thus the total energy of about 10^7 supernovae would be demanded to explain the phenomena if stars were involved.

The mass equivalent of this energy is about 100–1000 $M_{\odot}$.

In some radio sources there is evidence of interaction between two galactic systems, suggesting that a fraction of the energy of collision, if it can be converted, is available as an energy source. However, there is no evidence that in M87 any collision process is taking place. It may be that the system is in the process of formation and that this is a process of energy loss which is required. It is very rich in globular clusters, and, by measuring the colors of some of these and comparing them with the globular clusters in our own Galaxy, it might be possible to make an estimate of the age of the system. The richness of M87 in globular clusters has led Shklovsky to suggest that perhaps the energy source arises in collisions between globular clusters. This possibility should be investigated further, in order to see whether the rate of collisions with the very small cross-sections for stellar encounters is sufficient. It is probable that at this epoch in its evolution the stellar population of the jet is small. The absence of stellar absorption lines in the jet spectrum suggests this. Also, if the total amount of radiation from stars in the jet were comparable to the amount of synchrotron radiation, the total degree of polarization would be small. This suggests that there are $\ll 10^{41}/10^{33}$ stars in the jet.

Finally, it remains to speculate on one other possible energy source—the presence of antimatter. If this were present in a separate galactic system, there is no known observational method which would enable us to detect it. However, theoretical arguments suggest that if antimatter were present in any gaseous medium with a density of the order of the interstellar density in our own Galaxy ($\simeq 10^{-24}$ gm/cc), its rate of reaction with the normal matter would be such that, in a time scale $\ll 10^9$ years, the constituent in the smaller proportion would be reduced to a negligible fraction. However, if in M87 a globular cluster consisting of stars completely composed of antimatter were captured after it had been moving in the intergalactic medium, where the reaction rates are quite small, it would eventually collide with one of the globular clusters of normal matter. In this case very few stellar collisions would be made, but in a stellar collision the rates of the reactions would probably become so fast that the whole of the mass would be converted to mesons with energies of 10^8–10^9 ev and hence to electrons, positrons, neutrinos, and gamma radiation. This is not entirely certain, since it is possible that the pressures set up in the interactions between the outer regions of the stars would become so large that the remaining material would be separated again. The threshold for the production of nucleon-antinucleon pairs is too high for any proton or antiproton component to be produced in such an interaction, so that the total particle energy necessary to produce the synchrotron emission would be ϵ and not $\epsilon(M/m)$. The discussion given in Section VI would then become superfluous. Only one or two stellar encounters would be required to produce the electron-positron component, which would then have to be further accelerated, perhaps by the Fermi mechanism in the turbulent magnetic fields.

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