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THERMAL CONDUCTION AND HEATING BY NONTHERMAL ELECTRONS IN THE X-RAY HALO OF M87

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ABSTRACT

A hydrostatic model for the X-ray halo around the giant elliptical galaxy M87 is presented. We show that by taking into account the processes of thermal conduction, and nonthermal heating by relativistic electrons in the radio lobes, a self-consistent hydrostatic model can be constructed. There is no need to invoke radiative accretion or the suppression of thermal conductivity.

Subject headings: galaxies: individual — galaxies: structure — hydrodynamics

I. INTRODUCTION

We present a model for the X-ray halo of the giant elliptical galaxy M87. Our model differs from previous models for this source in that we include the effects of nonthermal heating by relativistic electrons in the extended radio lobes (Lea and Holman 1978; Scott *et al.* 1980) and thermal conduction from the hotter outer parts of the halo. By taking these processes into account, we are able to construct a hydrostatic model that is consistent with the X-ray surface brightness and spectral observations.

In § II, we summarize the observations, with particular reference to the temperature and density profiles implied by the observations. In § III, we discuss the different terms in the energy equation and present a solution to the energy equation that is consistent with the observations.

II. TEMPERATURE AND DENSITY PROFILES

Observations of M87 by the *HEAO 1* and *HEAO 2* experiments allow the construction of reasonably accurate temperature and density profiles for the extended X-ray halo. For convenience we divide the halo into three regions: (I) an outer region of radius $r > r_1 = 8' = 1 \times 10^{23}$ cm; (II) an intermediate region with $1'.5 \lesssim r \lesssim 4'$; and (III) an inner region with $r \lesssim 1'.5$.

The observations of Lea *et al.* (1981), Lea, Mushotzky, and Holt (1982), and Fabricant and Gorenstein (1982) indicate that the outer region is nearly isothermal with a temperature $T \approx 3.5 \times 10^7$ K. For an isothermal gas, the density profile can be derived from the surface brightness profile in a straightforward manner using the *Einstein* IPC data. Fabricant and Gorenstein (1982) find $n \propto r^{-1.3}$, consistent with findings of Schreier, Gorenstein, and Feigelson (1982), who used *Einstein* HRI data.

In the inner region, the observations of Fabricant and Gorenstein (1982) and Schreier, Gorenstein, and Feigelson (1982) indicate that the density profile flattens to approximately $n \propto r^{-1.1}$. The temperature decreases from about 3.5×10^7 K at $4'$ to about 1.6×10^7 K between $3'$ and $1'$ and eventually drops to as low as 6×10^6 K (Lea, Mushotzky, and Holt 1982; Canizares *et al.* 1982). The X-ray spectroscopy results of Canizares *et al.* (1982) are consistent with an emission measure ξ such that the logarithmic derivative $T(d\xi/dT) \propto T$ between 4 and 10×10^6 K. From this relation we can extract the dependence of T on r: $d\xi/dT = (d\xi/dT)/(dT/dr)$, so $T(d\xi/dT) = (d\xi/dr)/(d \log T/dr)$. $d\xi/dT = 4\pi n^2 r^2$, so $T(d\xi/dT) \propto n^2 r^3$. Since $T(d\xi/dT) \propto T$, we have $T \propto n^2 r^3 \propto r^{0.8}$ for $n \propto r^{-1.1}$.

The density and temperature profiles inferred from the data can be summarized as follows:

Region (I) $r > 4'$:
$n \propto r^{-1.3}$
$T \approx \text{constant} \approx 3.5 \times 10^7$ K;

Region (II) $1.5 < r < 4'$:
$n \propto r^{-1.2}$
T increasing with r from $\approx 1.8 \times 10^7$ K to $\approx 3.5 \times 10^7$ K;

Region (III) $r < 1'.5$:
$n \propto r^{-1.1}$
$T \propto r^{0.8}$.

III. HYDROSTATIC MODEL WITH THERMAL CONDUCTION AND NONTHERMAL HEATING

a) *Equations*

The equations governing the equilibrium of a hydrostatic halo are

$$dp/dr = -\rho\, d\phi/dr \tag{1}$$

$$\frac{1}{r^2}\frac{d}{dr}\left(r^2 K T^{2.5}\frac{dT}{dr}\right) + q_H = n^2 P(T), \tag{2}$$

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where ρ is the gas density, p is the pressure, ϕ is the gravitational potential, K is the thermal conductivity constant $= 6 \times 10^{-7} b$ ergs cm^{-3} s^{-1} (K)$^{3.5}$, q_H is the heat input cm^{-3}, and $n^2 P(T)$ is the radiative energy loss cm^{-3}. The term b is a correction factor < 1 that accounts for the reduction of thermal conductivity by magnetic fields.

For the temperature and density profiles given above, the mean free path is less than one-tenth the radius for $r \lesssim 200'$, so the assumption that thermal conduction can be described by the classical formulas is valid.

The radiative energy loss term is a slowly varying function of temperature. For temperature between ~ 2–30×10^6 K, and cosmic abundances of the elements, $P(T) \approx 10^{-22.5} (T/10^7 \text{ K})^{-1/2}$ is for our purposes an adequate description of the loss rate given, for example, by Raymond (1982).

The heating rate can be estimated from the work of Scott *et al.* (1980). They show that the heating rate by relativistic electrons can be many orders of magnitude larger than the normal Coulomb heating rate when collective effects such as the relativistic two-stream instability are important. Their estimate for the heating rate is

$$q_H = \eta (n_r ec)^2 / 3, \tag{3}$$

where n_r is the number density of relativistic electrons and η is the anomalous resistivity:

$$\eta \approx (n_r / n\gamma_{\min}) \omega_p, \tag{4}$$

ω_p is the plasma frequency $= 6 \times 10^4 \eta^{1/2}$, and $\gamma_{\min} mc^2$ is the low-energy end of the relativistic electron distribution which is assumed to follow a power law for $\gamma > \gamma_{\min}$. Using equations (3) and (4) and evaluating the constants,

$$q_H = 10^{-3} (n_r/n)^3 n^{1.5} / \gamma_{\min} \text{ ergs cm}^{-3} \text{ s}^{-1}. \tag{5}$$

We can estimate n_r from the observations of the extended radio lobes (Kotanyi 1980; Dennison 1980; Andernach *et al.* 1979). For example, consider the inner lobes. These lobes have an angular size of slightly more than 1′, corresponding to a linear size of about 5 kpc. If the electron spectrum extends down to $\gamma_{\min} = 500$, corresponding to synchrotron frequencies of about 10 MHz, then for an assumed magnetic field strength of 4×10^{-6} gauss, $n_r = 3 \times 10^{-8}$, and $q_H = 2 \times 10^{-26}$ ergs cm^{-3} s^{-1}. Unfortunately, this estimate can only be a rough one, since n_r depends on uncertain quantities such as $\gamma_{\min}$ and the magnetic field strength.

A similar calculation for the outer lobes yields heating rates about one or two orders of magnitude lower in the outer lobes. In view of the uncertainties in estimating the heating rate, we assume the following form:

$$q_H(r) = q_H(r_1)(r/r_1)^{-2.6} \qquad r \lesssim r_1 = 1'.5$$
$$= 0 \qquad r \gtrsim r_2 \tag{6}$$

with $q_H(r_1) = 1 \times 10^{-26} q_{-26}$ ergs cm^{-3} s^{-1}.

This is roughly the amount of heating needed to explain the observed temperature profile in the central region. Without heating, the temperature drops too rapidly in the central region (Takahara and Takahara 1981).

We have assumed a hydrostatic model. Would a radiative accretion model fit the data equally well? It would not, if the accretion is to have any effect on the energy balance of the gas. The accretion term in the energy balance can be shown to have the functional form $q_{\rm acc} = q_{\rm acc}(r_1)(r/r_1)^{\gamma-3}$, where $T = T_1(r/r_1)^{\gamma}$. In the outer region, $\gamma \approx 0$ so $q_{\rm acc} \propto r^{-3}$, whereas $q_{\rm rad} \propto r^{-2.6}$, since $n \propto r^{-1.3}$. In the inner region, $\gamma \approx 0.8$, so $q_{\rm acc} \propto r^{-2.2}$, whereas $q_{\rm rad} \propto n^2 T^{-1/2} \propto r^{-2.6}$, since $n \propto r^{-1.1}$ in the inner region. So, if $q_{\rm acc} = q_{\rm rad}$ for small r, the approximate equality will also hold for large r. The effect will be to reduce the importance of radiative losses at all radii. If this reduction is significant, then conduction from the hot outer regions will maintain an approximately isothermal halo all the way in to very small radii, contrary to the observations. Binney and Cowie (1981) recognized this difficulty; thus, they postulated circumferential magnetic fields which reduced the thermal conductivity by a factor of ~ 1000, an assumption which they believe is supported by radio observations indicating that the magnetic field is approximately circumferential in the plane of the sky around M87. The immediate geometrical implication of the thousand fold reduction in radial thermal heat flux is that the average ratio of the radial to total magnetic field $\langle B_r/B \rangle \sim 10^{-3}$ *throughout* the volume of the X-ray emitting plasma, where the averaging is performed on spherical shells. Now the observed axial symmetry of the halo emission (Schreier, Gorenstein, and Feigelson 1982) argues that local departures of the field component ratio from the above mean are small; thus, if the thousand fold heat flux reduction is to be maintained, then $B_r \ll B$ almost everywhere within the halo. The radio data (which only yield information on the projected magnetic field in the plane of the sky) are consistent with this inequality but do *not* require it (Andernach *et al.* 1979; Dennison 1980). Furthermore, it is not obvious what mechanism could lead to $B_r/B \ll 1$ throughout a volume of radius $\gtrsim 200$ kpc. The required field geometry is highly ordered, with field lines lying (with only small departures) on concentric spherical shells. At $r = 4'$, the gas pressure $2nkT$ is a factor of 100 greater than the magnetic pressure, assuming $B = 4 \times 10^{-6}$ gauss, a reasonable upper limit in view of limitations due to Faraday depolarization

(Andernach *et al.* 1979; Dennison 1980). Since the gas pressure is much greater than the magnetic pressure, the maintenance of $B_r/B \ll 1$ requires that gas motions within the halo are largely confined to spherical shells. Any turbulent motions would have to be highly anisotropic because they would otherwise isotropize the field. These various constraints on any model for heat flux inhibition make it very implausible that a self-consistent model with a thousand fold reduction in the conductivity can be constructed. However, it is quite possible that the conductivity could be reduced by a factor of $\sim 3-10$. In view of the evidence for a partially circumferential magnetic field, we assume below that the heat flux is reduced by a factor of 3, i.e., we take $b = 0.33$.

b) Solution to the Energy Equation

The solution to the pressure balance equation involves the gravitational potential, which is not well known. Rather than present solutions for an arbitrary potential, we solve only the energy equation. This solution could then be used to determine a self-consistent form of the gravitational potential after the manner of Fabricant and Gorenstein (1982).

We solve the energy equation in regions II and III by assuming that $n \propto r^{-1.25}$. Since the temperature dependence of the conductive term is much stronger than the radiation term, we assume $P(T) = \text{constant}$. We find

$$T = T_0\{1 + [(L_H - L_R(1))/L_C(0)][(r_0/r) - 1] - [4L_R(0)/L_C(0)][(r_0/r)^{0.5} - 1]\}^{2/7}, \quad (7)$$

where $r_0 = 8' = 1 \times 10^{23}$ cm; $T_0 = 3.5 \times 10^7$ K;

$$L_H = 2 \times 10^{42} q_{-26} \text{ ergs s}^{-1};$$

$$L_R(1) = 8\pi n_1^2 r_1^3 P(T_1) = 5 \times 10^{42} \text{ ergs s}^{-1}; \quad (8)$$

$$L_R(0) = 4\pi n_0^2 r_0^3 P(T_0) = 5 \times 10^{42} \text{ ergs s}^{-1};$$

and

$$L_C(0) = (8\pi/7) r_0 k T_0^{3.5} = 5 \times 10^{43} b \text{ ergs s}^{-1}.$$

A good fit to the temperature profile for $r > 1.5$ is obtained by choosing $q_{-26} = 4$ and $b = 0.33$.

For region III ($r < 1\rlap{.}'5$), the conductive term becomes negligible, so the energy equation is just a balance between heating and radiation. Using equations (2) and (6), and $P(T) = P(T_1)(T/T_1)^{-1/2}$, we find

$$T/T_1 = [n_1^2 P(T_1)/q_H(r_1)]^2 (r/r_1)^{0.8}. \quad (9)$$

The fit to the data is good, as it should be, since we adjusted the heating term to make a good fit. However, as we have indicated, the heating function we have chosen is a plausible one, suggested by both theoretical and observational work. Therefore, we feel that a self-consistent hydrostatic model for the X-ray halo is not only a possible model, but the most plausible one. It has the added attraction that it ties together the hitherto unrelated radio and X-ray observations.

IV. RELATIONSHIP BETWEEN THE RADIO LUMINOSITY AND X-RAY LUMINOSITY

We can use equations (2) and (5) to derive a relation between the radio and X-ray luminosity in region III. The heat reduction term is negligible there, so $q_H = q_{\rm rad} = n^2 P(T)$. Using equation (5), we find

$$n \propto n_r^{6/7} [P(T)]^{-2/7}. \quad (10)$$

If we assume that the energy spectrum of relativistic electrons extends unchanged down to $\gamma_{\min}$, then n_r can be related to the low-frequency radio emission, L_R, and the magnetic field: $L_R \propto n_r B^{s+1} \nu^{-s}$, where s is the radio spectral index. The X-ray luminosity $L_x \propto n^2 P(T) f(\Delta E, T)$, where $f(\Delta E, T)$ gives the fraction of the total power that is radiated in the X-ray band. For temperatures of interest, $P(T) f(\Delta E, T) \approx \text{constant}$, so $L_x \propto L_R^{12/7} B^{-12(s+1)/7}$, where s is the radio spectral index. If the magnetic field is some constant fraction of the equipartition magnetic field, then $B \propto L_R^{2/7}$. Thus,

$$L_x \propto L_R^{12(5-2s)/49}.$$

For a spectral index $s = 0.9$, $L_x \propto L_R^{0.8}$. In this connection, we note the comment of Schreier, Gorenstein, and Feigelson (1982) that the extended X-ray morphology bears a striking resemblance to the radio morphology.

Finally, we speculate as to what happens when the heating turns off. A heating rate $\sim 2 \times 10^{-26}$ ergs cm^{-3} s^{-1} implies a lifetime $\approx 10^7$ yr for the low energy relativistic electrons. If these electrons are not replenished, then the temperature will drop rapidly in the inner region. This means that the pressure will drop in the center to the point where an accretion flow would begin. In principle, the halo could remain in this state. However, an accretion flow is not consistent with the observations, unless heat conduction is suppressed by a factor of ~ 1000. Either we are observing M87 at a special time in its existence, when the heat source is turned on, or radiative cooling in the center is somehow related to the production of relativistic electrons (Silk 1976; Cowie and Binney 1977; Fabian and Nulsen 1977; Mathews and Bregman 1978). We propose that the latter is the case. This idea is supported by the observations of other clusters of galaxies, which show that an excess density—hence excess radiative cooling—in the center of a cluster is well correlated with a central radio source (Jones and Forman 1982).

A rough outline of the behavior of halos with high central density might go like this: if the source develops a high density in the inner region, it cools. Pressure gradients develop, and an accretion flow begins. The accretion flow somehow generates relativistic electrons. These electrons heat the gas, shutting off the accretion flow until the electrons lose their energy, at which time the accretion flow begins again, etc.

V. SUMMARY

We have constructed a hydrostatic model for the X-ray halo of M87 that is consistent with the observations. The model takes into account heating by relativistic electrons in the radio lobes and thermal conduction from the hotter outer regions of the halo. There is no need to invoke radiative accretion or the suppression of thermal conductivity by large factors. This model offers an explanation for the observed conduction between X-ray and radio morphology in the inner parts of the halo. In general, we expect X-ray halos with a high central density to be in a relaxation-oscillation state in which radiative accretion is coupled to the generation of nonthermal electrons.

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