Magnetic Fields and Turbulence in the Center of M87

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Abstract. Faraday rotation data reveal that the inner core of M87 has a strong, ordered, magnetic field. This field is located in front of the inner radio lobes, and has a pressure at least as large as that of the thermal X-ray plasma. This field must be supported by fluid turbulence in the core region: the question is, what drives the turbulence?

1 Radio Polarization Imaging of the Inner Lobes

Radio polarization provides a unique way to determine the magnetic field in the gas surrounding a synchrotron source. We measure the rotation angle of linearly polarized rotation, which is related to the plasma density and magnetic field along the line of sight through

$$\chi = (\mathrm{RM})\lambda^2 \ ; \qquad \mathrm{RM} = \int n\mathbf{B}\cdot d\mathbf{l} \simeq 810 n \langle B_{\|} \rangle L \ \mathrm{rad/m}^2 \tag{1}$$

Here, B in μG, L in kpc, n in cm^{-3} and RM refers to Rotation Measure. It is important to note that we do not measure the full magnetic field, but only the algebraic (signed) mean of the line of sight component of that field.

Elsewhere in this meeting Owen (1997) has described the radio structure of the inner lobes of M87. In Fig. 1 we show our new VLA image of the rotation measure (which improves on our previous work, Owen, Eilek & Keel (1989), by extending the frequency baseline). Several features are worth noting.

- The rotation arises from foreground plasma, rather than from within the radio source. If this were not the case, the simple dependence of χ on λ^2 would be violated.
- The RM is ordered, not random, across the source, and is generally positive. It has RM $\sim$ 750-1000 rad/m^2 and projected transverse scale $\sim$ 0.5-1 kpc.
- There is a high-RM filament in the east lobe of the source, with RM $\sim$ 8000rad/m^2 and projected width $\lesssim$ 0.1kpc.
- There is a general trend for the RM to increase away from the core. In particular, the RM is much lower, $|\mathrm{RM}| \lesssim$ 100rad/m^2, and negative, in front of inner part of the jet.

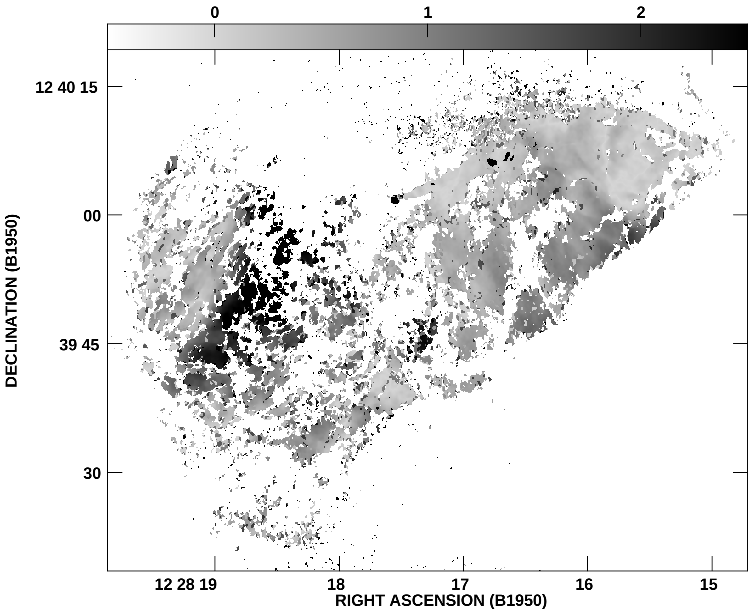

Fig. 1. Rotation measure image of the inner lobes of M87, based on 4 frequencies around 5 GHz and 4 frequencies around 8 GHz. The grey scale runs from -500 rad/m^2 to +3000 rad/m^2. The narrow, high-RM filament in the eastern lobe is in the blackest part of this figure.

2 What is the Nature of the Magnetic Field?

2.1 Evidence from Faraday Rotation

The RM image tells us that there is an ordered magnetic field in the inner core. We start with the simplest geometry in order to estimate the field strength. That is, we assume the ordering scale along the line of sight is similar to the transverse scale, $\sim 0.5-1$ kpc, and that there is no significant algebraic cancellation. This does not require a particular model of the magnetic field, but only that the covering factor of the field structures is of order unity.

For the gas density, we estimate $n \sim 0.08$ cm^{-3} from Nulsen & Böhringer (1995). We assume the RM arises from magnetic fields in the thermal X-ray loud plasma.[1] Taking a typical RM$\sim$ 750rad/m^2, and adding a factor $\sqrt{3}$ to estimate projection effects, we find $B \sim 20 - 50\mu$G. Comparing this to the "pressure equipartion" field, $B_p \sim 25 - 30\mu$G (Eilek 1997a), we find that the *typical* field in the inner core is dynamically significant.

[1] The RM screen is likely to sit inside of the extended radio lobes, Eilek 1997a. If the lobe density is lower than this value, then our derived fields are *lower limits*.

Similar calculations for the high-RM filament give $B \sim 2$ mG here, if the internal density is assumed to be the ambient density of the X-ray plasma. Owen, Eilek & Keel (1989) searched for Hα emission and X-ray excesses at the location of this filament, and found no evidence for density higher than the ambient value. Thus, this filament is clearly strongly overpressured relative to its surroundings.

What of the low-RM patch in front of jet? We have two options: either the source sits in a central "hole" in the magnetic field, or the jet lies in front of much of the inner radio lobe, and that the RM is closely associated with this radio lobe.

2.2 Evidence from Depolarization

The polarization data also tell us that, in addition to large-scale order in the magnetic field, the field has a small-scale structure, on scales $\lesssim 10$ pc.[2] In particular, we find the source is depolarized: the fractional polarization is smaller at longer wavelengths.

Low polarization at a given frequency comes about because of gradients in the direction of the linear polarization of the synchrotron radiation, on a scale smaller than the radio beam (~ 8 pc). The dependence on wavelength tells us that this is caused by gradients in the rotation measure, rather than intrinsic emissivity gradients in the radio loud plasma. Images of M87 in polarized emission (shown in Zhou 1997) show short, unpolarized *filaments*, of width $\sim$ beam size, at both 5 and 8 GHz. These dark filaments are more numerous at 5 GHz, so that the source is depolarized. The RM gradients must occur within these filaments. These filaments can be unresolved magnetic flux tubes with helical magnetic fields. Alternatively, the filaments may be thin interfaces between regions of uniform field. Either one will depolarize if the field gradient scale is smaller than a beam size.

2.3 Possible Models of the Magnetic Field

We can now compare the data to existing models of magnetized plasma. Because of the large-scale order, we can rule out the old, simple picture of a random field, consisting of many turbulent "cells" (Burn 1966). We can rule out the simple cooling-flow model which predicts many radially stretched loops (Soker & Sarazin 1989), for the same reason.

Bicknell, Cameron & Gingold (1990) have suggested that the RM in CygA arises from magnetic fields in the radio-loud plasma, which have mixed with the ambient thermal gas, in a skin of the radio source. This picture has problems explaining trends seen in all cluster-center radio sources. It does not easily account for RM asymmetry or the lack of limb brightening, and it

[2] The detection of power on both small and large scales is, of course, characteristic of turbulence.

may have trouble with the slow rate of cross-field mixing and the need for strongly overpressured thin skins (Eilek, Owen & Wang 1997). On the other hand, in the case of M87, the low RM in front of the jet may suggest that the inner lobes sit behind the jet, in which case the RM would have come from a region (skin?) between the inner lobes and the jet. Thus, we cannot rule out this model for this galaxy.

The picture we favor, however, is that the magnetic field is maintained, and shaped by, turbulence in the core region. We have direct evidence of transonic velocities very close to the core. The emission line clouds move at $\sim$ 200km/s (Sparks, Ford & Kinney 1993),which gives a Mach number $\mathcal{M} \sim 0.4$ in a plasma at $T \sim 1.5$keV. The clouds are very likely to represent the velocity field in the surrounding X-ray gas. In addition, observations of the outer radio halo strongly suggest that the entire Virgo core is disordered and turbulent (Eilek 1997a). Magnetic fields supported by turbulence can reach a level,

$$\frac{B^2}{8\pi} \lesssim \frac{1}{2}\rho v_t^2 \tag{2}$$

For the conditions in the core of M87, this dynamo-supported field can be estimated as $B \lesssim 25\mathcal{M}\ \mu$G. Thus, Mach 1 turbulence, if it exists, can produce fields comparable to those observed. We think it likely this is the origin of the fields, and that they exist throughout the inner Virgo core.

The geometry of a magnetic field in a turbulent plasma depends on the nature of the turbulence. Isotropic turbulence leads to intermittent magnetic fields: the strong field, satisfying (2), tends to be localized in filaments or flux ropes (e.g., Ruzmiakin, Sokoloff & Shukurov 1989, Miller *et al* 1996). If the turbulence is helical (meaning that it has a particular small-scale anisotropy), it also supports magnetic fields ordered on large scales. These fields may well be in a force-free state (Taylor 1986). Their geometry can be described as nested toroids, which lead to a central "hole" in the RM image (Eilek 1997b). The observations in hand do not allow us to distriminate between helical or symmetric turbulence. However, the depolarization data seem to us to support the picture of small-scale intermittent fields.

3 The Virgo Core Compared to Other Clusters

Whatever the details of the dynamo, the data tell us that the inner core of M87 is magnetized, at a level comparable to the thermal gas pressure. This striking result is not unusual for cluster-center galaxies. Ten such galaxies have been imaged in rotation measure. (The situation is described in Eilek, Owen & Wang 1997). The radio sources range in size from a few kpc to $\sim$ 150 kpc. Their cooling cores range in strength from $\sim 600 M_\odot$/yr, to $\lesssim 1 M_\odot$/yr. All ten sources show ordered RM (projected scales $\sim$ few - 20 kpc), and *all show large fields* (ratio of magnetic pressure to gas pressure $\sim 0.1 - 10$). Thus, the X-ray gas in M87 is not unusual: it seems very typical in having a dynamically significant magnetic field embedded in its core.

4 Turbulence in the Virgo Core

We have shown that the very center of M87 contains a strongly magnetized, thermal plasma; we have argued that transonic turbulence must be what supports this field. How extensive is this active region? We have no direct evidence for magnetic fields in the X-ray gas on scales larger than the inner lobe. However, we have strong indirect evidence from the outer radio halo and the X-ray image that the entire Virgo cluster core, on a scale $\lesssim$ 40-50 kpc, is disordered and stirred up. Thus, it does not seem unjustified to assume that this entire core region is turbulent, possibly at the transonic level. What does this require of the energy budget?

Turbulence will decay if it is not driven. Scaling arguments show that the decay time $\tau_t \sim f\lambda_t/v_t$, where λ_t, v_t are the characteristic (outer) scale and velocity of the turbulence, and f is a fudge factor on the order of a few. Estimating $\lambda_t \sim 1 - 10$ kpc, we find $\tau_t \sim 25 - 100$ Myr. This is a short time; the turbulence must be driven.

What driving power is needed? The X-ray data (Nulsen & Böhringer 1995) tell us that the total thermal energy in this region is $U_{th} \simeq 1 \times 10^{59}$erg. The turbulent energy is then $U_t \simeq \mathcal{M}^2 U_{th}$. Dividing the turbulent energy by its decay time, we find the necessary driving power: $P_t \simeq 3 \times 10^{44} \mathcal{M}^3 / \lambda_{t,kpc}$erg/s. This is very similar to current estimates of the power deposited by the radio galaxy, and also to the power deposited in the core by large-scale motions in the cluster (as summarized in Eilek 1997a). This reinforces our picture of the Virgo core being an active, turbulent region.

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