LIMITS ON THE DIFFUSE RADIO AND HARD X-RAY EMISSION OF ABELL 2199

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ABSTRACT

The Westerbork Northern Sky Survey (WENSS) and the NRAO/VLA Sky Survey (NVSS) were used to determine an upper limit to the diffuse radio flux from the nearby cluster Abell 2199. For the entire cluster, this limit is \(<3.25\) Jy at 327 MHz from WENSS; for the inner 15′ radius, the limit is \(<168\) mJy at 1.4 GHz. These limits are used to constrain the cluster magnetic field by requiring that the radio flux be consistent with the hard X-ray (HXR) flux observed by BeppoSAX, assuming that the observed HXR excess is due to inverse Compton (IC) scattering of cosmic microwave background photons by relativistic electrons in the intracluster gas. We find that the magnetic field must be very weak (\(<0.073\) \(\mu G\)) in order to avoid producing an observable radio halo. We also consider the possibility that the HXR excess is due to nonthermal bremsstrahlung (NTB) by a population of suprathermal electrons which are being accelerated to higher energies. We find that a NTB model based on a power-law electron momentum distribution with an exponent of \(\mu \approx 3.3\) and containing about 5% of the number of electrons in the thermal ICM can reproduce the observed HXR flux.

Subject headings: cosmic rays — galaxies: clusters: individual (Abell 2199) — intergalactic medium — magnetic fields — radio continuum: galaxies — X-rays: general

1. INTRODUCTION

Abell 2199 is a nearby (\(z = 0.0303\)) X-ray cluster. It contains a cooling flow which is centered on the cD galaxy NGC 6166, which is also a strong radio source (3C 338). Recent X-ray observations of the cluster with BeppoSAX (Kaastra, Bleeker, & Mewe 1998; Kaastra et al. 1999) found evidence for an excess of hard X-rays above that expected from the thermal emission of the hot intracluster gas. There are several possible interpretations of this hard tail to the X-ray luminosity. One is that the excess is caused by inverse Compton (IC) scattering of cosmic microwave background (CMB) photons by highly relativistic cosmic ray electrons located in the intracluster medium (ICM) (Rhephael 1979; Kaastra et al. 1999). Another is that the excess is produced by nonthermal bremsstrahlung (NTB) by subrelativistic but suprathermal electrons which are undergoing acceleration in the ICM (Kaastra et al. 1998; Enßlin, Lieu, & Biermann 1999; Sarazin & Kempner 1999). If the first explanation is correct, the same relativistic electrons should produce diffuse radio synchrotron emission as long as the ICM contains a magnetic field which is not too small. As a test of the IC model, we search for diffuse radio emission from this cluster using the Westerbork Northern Sky Survey (WENSS; Rengelink et al. 1997) and the NRAO/VLA Sky Survey (NVSS; Condon et al. 1998). We assume \(H_0 = 50\) km s\(^{-1}\) Mpc\(^{-1}\) and \(q_0 = 0.5\) throughout.

2. LIMITS ON DIFFUSE RADIO HALO

We searched for diffuse radio emission from Abell 2199 using the WENSS 92 cm radio survey and the NVSS radio survey at 20 cm. The WENSS images have a synthesized beam of 54′′ × 85′′ at the declination of Abell 2199. The typical noise level is 3.6 mJy beam\(^{-1}\). WENSS interferometer observations should be sensitive to radio emission on scales of less than \(\sim 1\)′. The NVSS synthesized beam is 45′′ × 45′′. The typical noise level is 0.45 mJy beam\(^{-1}\). The NVSS is sensitive to emission on scales of less than 15′. At the redshift of Abell 2199, a typical cluster core radius of 200 kpc corresponds to 3.5′, while an Abell radius of 3 Mpc subtends 58′. Thus, the WENSS observations should be sensitive to a diffuse radio halo in the cluster if it is smaller than the cluster Abell radius, while the NVSS should be sensitive to a halo smaller than 775 kpc.

The WENSS survey gives a source catalog (Rengelink et al. 1997), which contains 22 sources which lie within half a degree (the largest angular scale not resolved out by the interferometer used in the survey) of the center of the cluster. We adopt the position of the central cD galaxy NGC 6166, R.A. = 16\(^{h}\)26\(^{m}\)55\(^{s}\), Dec. = +39°39′37″, as the center of the cluster. The strongest radio source is 3C 388 which is associated with the central cD galaxy. None of these sources is extended on the scale of the cluster, so we do not include this emission in the measurement of the diffuse cluster radio emission. To search for diffuse radio emission, we used the survey radio image to determine the total radio flux from a circle of radius 30′ (1.55 Mpc at the distance of Abell 2199). We then subtracted from this measured flux the sum of the integrated fluxes of all sources in the WENSS catalog within this region. This residual flux was found to be 3.25 ± 0.21 Jy.

However, the cD galaxy in Abell 2199 is the very strong radio source 3C 338, with a peak-to-rms brightness ratio of 3190 in WENSS. Slight instrumental variations between receivers in a radio interferometer cause the region immediately around a bright source with such a large peak-to-rms ratio to have both an increased rms noise level and a systematic positive flux from uncleaned sidelobes in the absence of real diffuse emission (Condon et al. 1998). This systematic excess flux varies from source to source in WENSS. We did an inspection of several other bright sources in the surveys and found that the effect is consistently between about 8 and 12% of the peak intensity of the source. The residual flux in Abell 2199 is approximately 12% of the peak flux of the cD, so we must treat this residual as an upper limit on the diffuse synchrotron flux from the cluster rather than as a detection of diffuse emission. If we subtract our best estimate of this systematic effect from the measured flux, the upper limit on the flux would be reduced by at least a factor...
of five. However, due to the uncertainty in the magnitude of this baseline offset, we use the more conservative value without attempting to remove the effect of the offset baseline. Thus, our upper limit to the diffuse radio flux of Abell 2199 at 92 cm is 3.25 Jy.

The dynamic range of the NVSS is more sensitive, and the cD is better resolved than in the WENSS observations, so the peak-to-rms of the cD is not as great. There is still some noticeable uncleaned sidelobe structure in the image, but it is relatively minor. Since the NVSS resolves out structures larger than 15′, we used the same procedure as with WENSS, but restricted to a 15′-circle. We measure a residual flux of $-97 \pm 56$ mJy. The small negative flux appears to be caused by the uncleaned sidelobes and is consistent with zero diffuse emission. From this, we can rule out the existence of a radio halo within the central 750 kpc of the cluster. The 3-$\sigma$ upper limit of the diffuse flux in the NVSS survey is $<168$ mJy. The WENSS limit is more conservative since, unlike the NVSS, no flux is resolved out in the region containing the HXR emission observed by BeppoSAX.

3. IC X-RAY EMISSION AND THE CLUSTER B FIELD

If the relativistic electrons in the cluster have a power-law energy distribution, then both the radio synchrotron and the IC hard X-ray spectra are expected to be power laws in frequency with the same spectral index (e.g., Rephaeli 1979). Kaastra et al. (1998, 1999) fit the X-ray spectra from BeppoSAX with a power-law spectrum excess to the thermal emission from the ICM. In Kaastra et al. (1999), a single power-law excess was fit across the entire X-ray band, roughly from 0.1–100 keV. The total luminosity in this band was $(1.30 \pm 0.32) \times 10^{44}$ erg s$^{-1}$.

The cluster Abell 2199 shows both a hard X-ray excess and an extreme ultraviolet (EUV) or soft X-ray excess (Lieu, Bona- mente, & Mittaz 1999). In Kaastra et al. (1999), the authors argue that both the EUV and HXR excesses are nonthermal IC emission. The best-fit power-law photon spectral index was $\Gamma = 1.81 \pm 0.25$ for the entire spectral band 0.1–100 keV. This implies a flux of $S_{\text{HXR}} = (1.6 \pm 0.4) \times 10^{-11}$ ergs cm$^{-2}$ s$^{-1}$ in the HXR band, 10–100 keV.

If this hard X-ray emission is due to IC scattering of the CMB photons, then the predicted radio synchrotron flux is

$$S_{\nu} = 234 \left( \frac{S_{\text{HXR}}}{10^{-11} \text{ergs cm}^{-2} \text{s}^{-1}} \right) \left( \frac{B}{1 \mu G} \right)^{1.81} \times \left( \frac{\nu}{327 \text{MHz}} \right)^{-0.81} \text{Jy},$$

if the photon spectral index of the HXR emission is $\Gamma = 1.81$. Here, $S_{\text{HXR}}$ is the HXR flux in the 10–100 keV band, $B$ is the cluster magnetic field, and $\nu$ is the observed frequency.

If we use the observed HXR flux of Abell 2199 and our conservative upper limit on the radio flux at 327 MHz ($S_{\nu} < 3.25$ Jy), this implies a strong upper limit on the magnetic field of $B < 0.073 \mu G$. If we correct for the aforementioned instrumental excess radio emission near strong sources, we reduce the observed radio flux by a factor of $\sim 8$ and consequently reduce the maximum magnetic field by a factor of 2 to 3. Similarly, if the NVSS limit on a smaller radio halo at higher frequencies is used, the limit on the magnetic field is $B < 0.02 \mu G$. Thus, we have a conservative upper limit of $0.073 \mu G$, with the strong suggestion that the field must be even weaker. If we instead assume a more typical magnetic field of $1 \mu G$, the upper limit on the radio flux implies an upper limit to the inverse Compton HXR flux which is more than 100 times fainter than was observed with BeppoSAX.

4. NONTHERMAL BREMSSTRAHLUNG

Alternatively, the HXR excess observed in Abell 2199 might result from some other emission process. Perhaps the most likely possibility is nonthermal bremsstrahlung (NTB) from suprathermal electrons in the ICM (Kaastra et al. 1998; Enßlin, Lieu, & Biermann 1999; Sarazin & Kempner 1999). These might be electrons with energies $\gtrsim 10$ keV which are currently being accelerated up to much higher energies, either by shocks or by turbulent acceleration. Detailed models for NTB emission in clusters are given in Sarazin & Kempner (1999).

One feature of such models is that the excess emission spectrum should flatten at low energies, because the suprathermal population only contains electrons with energies which are higher than typical thermal energies (see Figure 1 below). Thus, one does not expect nonthermal bremsstrahlung to produce any EUV excess emission directly. It is also inappropriate to fit a single power-law spectrum to the NTB emission across the entire X-ray band 0.1–100 keV. On the other hand, Sarazin & Kempner (1999) show that a power-law does provide a reasonable fit to the spectrum of the HXR emission, 10–100 keV. In Kaastra et al. (1998), the HXR excess emission in Abell 2199 as seen in the BeppoSAX PDS was fit independently of any softer excess. This gave a flux of $S_{\text{HXR}} = (1.4 \pm 0.4) \times 10^{-11}$ ergs cm$^{-2}$ s$^{-1}$ in the 10–100 keV band. The best-fit power-law photon spectral index was $\Gamma = 2.5^{+0.1}_{-0.8}$. This is steeper than the spectral index found by fitting a power-law excess to the entire X-ray band (Kaastra et al. 1999), although the error bars overlap.

Let $N(p)dp$ be the total number of nonthermal electrons with normalized momenta in the range $p$ to $p + dp$, where $p$ is the momentum normalized to $m_c$. The simplest models for the nonthermal electrons in clusters have a power-law momentum distributions (Sarazin & Kempner 1999), with

$$N(p) = N_p p^{-\mu} \quad p \geq p_l.$$  

We will assume that the suprathermal population consists only of particles with momenta $p > p_l$, such that their kinetic energies exceed $3kT$ where $T$ is the temperature of the thermal ICM. If the cooling flow at the center of Abell 2199 is excluded, the mean ICM temperature is $T = 4.8 \pm 0.2$ keV (Markovitch et al. 1999b). This implies that $p_l = 0.24$.

For steep power-law momentum distributions ($\mu \gtrsim 3.5$), the nonthermal bremsstrahlung HXR emission is nearly a power-law with $\Gamma = 1 + \mu/2$ (Sarazin & Kempner 1999). For flat-topped momentum distributions, the NTB spectra are still approximately fit by power-laws, but the exponent is flatter than given by this expression. The observed spectral index of $\Gamma = 2.5$ between 10 and 100 keV is produced by a model with $\mu = 3.33$. The predicted nonthermal bremsstrahlung spectrum of this models is shown in Figure 1. The observed flux in the 10–100 keV band is reproduced by a model with $N_{p_0} = 3.88 \times 10^{28}$, which implies that the total number of nonthermal electrons is $4.6 \times 10^{31}$ if the electron spectrum extends to higher energies. This represents about 5% of the total number of thermal electrons in the intracluster medium in Abell 2199 (Mohr, Mathiesen, & Evrard 1999).

If the nonthermal electron distribution extends to much higher energies, HXR would be produced through IC by these higher energy electrons. In fact, if the electron spectrum is flatter than $\mu \lesssim 2.7$, more HXR emission is produced by IC than by NTB. However, for the steep electron spectrum in our NTB
model, IC by high energy electrons only contributes about 0.6% of the flux in the 10–100 keV HXR band. The small number of high energy electrons in this steep spectrum model also reduces the radio synchrotron emission. For a magnetic field of 1 \( \mu G \), the predicted radio flux is 0.73 Jy at 327 MHz. Thus, the predicted radio emission is consistent with our limit as long as \( B \lesssim 2 \mu G \).

**Fig. 1.** — The nonthermal bremsstrahlung hard X-ray emission of our model with a power-law momentum distribution with \( \mu = 3.33 \). The emitted spectrum is given as a function photon energy. The flattening of the spectrum at low energies is due to the cut-off in the suprathermal electron population at an energy of 3\( kT \).

On the other hand, with this steep electron spectrum, the model cannot reproduce the EUV or soft X-ray excess which has been observed in Abell 2199 (Kaastra et al. 1999; Lieu, Bonamente, & Mittaz 1999), either by NTB or IC emission. Apparently, a distinct population is needed to produce the observed EUV emission. Since the electrons which generate EUV by IC have long lifetimes comparable to cluster ages (Sarazin & Lieu 1998), it is possible that the EUV emission is produced by an older population of electrons, while the NTB HXR emission is due to electrons currently being accelerated.

**5. CONCLUSIONS**

We have used the WENSS and NVSS radio surveys to search for any diffuse radio emission (a radio halo or relic) associated with the cluster of galaxies Abell 2199. We do not detect any such emission. The best limit on any cluster-wide emission comes from the WENSS survey, which gives a limit of 3.25 Jy at 327 MHz. The limit would be considerably tighter were it applied by the limit on the radio flux is very weak. If we adapt our most conservative limit on the total diffuse radio flux of the cluster, it implies that the ICM magnetic field is \( B < 0.073 \mu G \). If we correct the radio limit for the uncleaned sidelobes of the central radio source 3C 338, or if we use the stronger limit on a centrally condensed radio halo (\( \lesssim 750 \text{kpc} \)) from the NVSS, then the limit on the magnetic field is smaller by a factor of about 3. These field limits are at least an order of magnitude smaller than the magnetic fields derived from Faraday rotation measurement towards individual radio galaxies (e.g., Feretti et al. 1995) or statistical samples of radio sources (Clarke 1999) in other clusters. Very strong Faraday rotation is detected toward the central radio source 3C 338 in Abell 2199 (Ge & Owen 1994), which implies the presence of a magnetic field which is about two orders of magnitude stronger than the limit we find for the diffuse field if the HXR emission is due to IC scattering. However, the field around 3C 338 might have been enhanced by compression or shear associated with the cooling flow at the center of the cluster (Soker & Sarazin 1990).

One possibility is that the magnetic field in Abell 2199 (and, presumably, other clusters) is very inhomogeneous, and the magnetic field and relativistic electrons are anticorrelated (Enßlin et al. 1999). This might occur because electrons in high magnetic field regions lose energy rapidly by synchrotron emission, and the remaining high energy electrons might be found preferentially in weak magnetic field regions. This model was proposed for the Coma cluster (Enßlin et al. 1999), where the observed IC HXR emission implies a lower value of the magnetic field than has been determined from Faraday rotation measurements (Fusco-Femiano et al. 1999).

If the intrachuster magnetic field and relativistic electrons are not anticorrelated, it is difficult to believe that the ICM magnetic field is as weak as required by the HXR flux. Of course, it is possible that the nonthermal HXR flux is in error, because of calibration uncertainties with BeppoSAX, or because of another hard X-ray source in the field of view, or because of a complex thermal structure in the ICM which produces a thermal HXR tail.

Alternatively, the HXR emission may be real, but not due to IC scattering of CMB photons. The most attractive alternative
emission mechanism may the nonthermal bremsstrahlung emission
by a population of mildly subrelativistic nonthermal electrons with energies of 10–1000 keV (Kaastra et al. 1998; ESSLIN,
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based on a power-law momentum distribution for the nonther-
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observations acceptably. With a power-law exponent this steep,
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