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THE X-RAY COOLING FLOW IN THE CLUSTER OF GALAXIES AROUND PKS 2354–35

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ABSTRACT

A position measured with the *HEAO 1* Scanning Modulation collimator suggested the group of galaxies surrounding the radio galaxy PKS 2354–35 as the identification of the bright, hard X-ray source 4U 0009–33 = 3A 2356–341 = 1H 2355–350. We confirm this identification with measurements of the position and spatial extent using the *EXOSAT* CMA detector. It shows centrally condensed X-ray emission which is distinctly asymmetric, with a core radius $\sim 7\'.3$ in a roughly N-S direction and $\sim 2\'.5$ in the E-W direction. A serendipitous *Einstein* IPC detection confirms the shape of this extent. The *EXOSAT* ME data are fitted by a thermal bremsstrahlung spectrum with a temperature of 3.7 ± 0.7 keV.

Previously, PKS 2354–35 had been found to be a cD galaxy in a small group at redshift 0.048. At this distance the 2–6 keV X-ray luminosity is 1.6×10^{44} ergs s^{-1}. Our own optical observations reveal strong, narrow (<1000 km s^{-1}) emission lines of [O II] and [N II] with luminosities $\sim 10^{41}$ ergs s^{-1}. Archival radio observations from the partially completed VLA discovered a 35″ long, jetlike component, nearly aligned with the major axis of the X-ray distribution. The high-frequency radio spectrum of the total source is very steep, with a spectral index of 1.6 in the 1.4–5 GHz band.

From the X-ray observations we deduce a strong accretion flow. The luminosity and core radius imply a central density at least 8×10^{-3} cm^{-3}. The central cooling time is no longer than 5×10^9 yr, and the mass accretion rate can be estimated roughly as 320 $M_\odot$ yr^{-1}.

Subject headings: galaxies: clustering — galaxies: individual (PK 2354–350) — galaxies: intergalactic medium — galaxies: X-rays

1. X-RAY OBSERVATIONS

1.1. *Introduction*

We are using data from the Scanning Modulation Collimator (MC) experiment (see Gursky et al. 1978; Remillard et al. 1986) on the first *High-Energy Astronomy Observatory* (*HEAO 1*) to locate and identify as many as possible of the bright (1 μJy at 3.6 keV), hard (2–10 keV) X-ray sources previously discovered in all-sky surveys. These objects have unique importance, analogous to the 3CR radio survey, because of their limited numbers and because their brightness makes them accessible to the most detailed study at all wavelengths. They will be targets of choice to study time variability and dispersive spectroscopy with future X-ray missions. Our specific primary objective is to complete identification of sources in the Large Area Sky Survey (LASS; Wood et al. 1984) catalog. This catalog contains 842 bright, hard X-ray sources observed simultaneously with the MC experiment during the first 6 month's sky scan.

This paper reports identification of 1H 2355–350 (originally discovered as 4U 0009–33; Forman et al. 1978) with a cluster of galaxies centered around an elliptical galaxy identified as the radio source PKS 2354–35. Clusters are a common identification of such bright sources, comprising 30 out of 68 extragalactic identifications in the *HEAO 1* sample of Piccinotti et al. (1982). Thermal bremsstrahlung from optically thin gas at $T \sim 10^8$ K is the dominant emission mechanism (see Forman & Jones 1982). The gas typically has a mass of the same order as that of the stars in the individual galaxies and fills a comparable volume (see Sarazin 1986, and references therein). X-ray imaging observations with *Einstein* (Forman & Jones 1982) have led to a morphological classification of clusters as either with or without a central dominant galaxy, and in each case according to three stages of increasing degree of dynamical relaxation. X-ray observations of clusters with a central dominant galaxy typically lead to the inference of short cooling time scales of the central gas, implying the need for an energy replenishment mechanism frequently attributed to inward mass flows with required rates of 10–1000 $M_\odot$ yr^{-1} (see Fabian, Nulsen, & Canizares 1984). Such flows may be related to powering central radio sources, or the formation of the central galaxy (Fabian et al. 1985); however, detailed accounting of the destination of the infalling mass has not yet been revealed observationally. The cluster surrounding the strong radio source PKS 2354–35 is in this category and is of particular interest as an example of a cooling accretion flow (see Fabian et al. 1984) in which the absence of spherical symmetry is a key feature (contrast to Stewart et al. 1984).

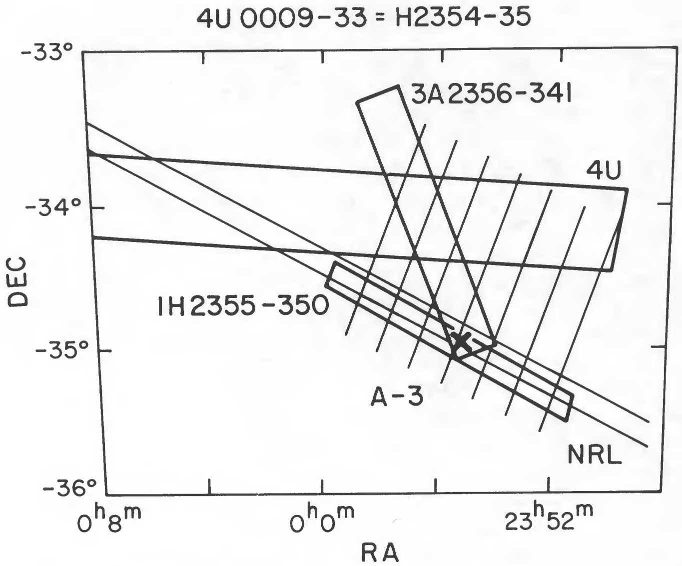

FIG. 1.—Nonimaging locations (*heavy boxes*) of the X-ray source 4U 0009−33 = 3A 2356−341 = 1H 2354−350, along with the modulation collimator multiple lines of position (designated A-3) from the 2′ FWHM collimator (MC2), and the line of position (light parallel lines) determined from our use of NRL data (denoted NRL). The heavy cross marks the position of PKS2354−35.

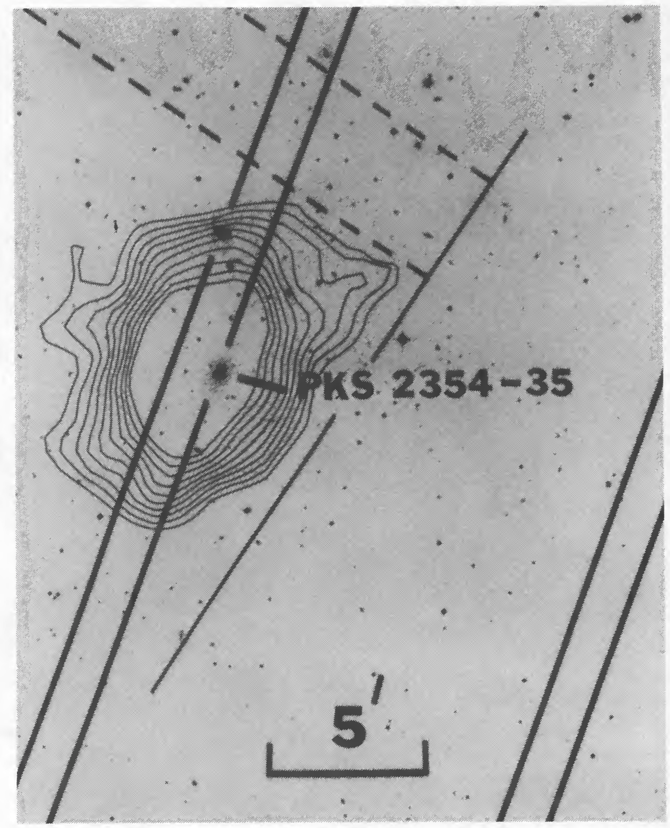

FIG. 2.—Finding chart showing the cD galaxy identified with PKS 2354−35 located inside an MC2 line of position. Contours are from a serendipitous observation at the edge of the *Einstein* IPC. The contours may be centered on the galaxy, to within the location precision of the IPC. The contours to the west and south are distorted by the edge of the IPC field (*light solid line*), while to the north and west they are distorted by shadowing of an IPC rib (*dashed parallel lines*).

1.2. *Location and Identification*

Figure 1 shows locations determined by mechanically collimated experiments. The original discovery by the *Uhuru* satellite was designated 4U 0009−33 (Forman et al. 1978) with a flux determined by the point summation technique of $4.0 \pm 0.5 \times 10^{-11}$ ergs cm^{-2} s^{-1} in the nominal 2–6 keV band. The *Ariel 5* source 3A 2356−341 was cataloged with a flux of $1.4 \pm 0.25 \times 10^{-11}$ ergs cm^{-2} s^{-1} (McHardy et al. 1981). The latter noted the presence of a group of galaxies in the southern part of the error box. The *HEAO-1* LASS catalog (Wood et al. 1984) reported 1H 2355−350 to have a flux of $3.4 \pm 0.3 \times 10^{-11}$ ergs cm^{-2} s^{-1} and noted the presence of the quasar 2357−348 near the error box. The lighter parallel lines marked "NRL" show the position restrictions we determined independently, using the *HEAO 1* LASS data furnished to us privately. All three of the fluxes quoted may be substantially inaccurate due to the displacement of the error box center from the identified object, to the possible presence of other sources in the relatively large mechanical fields of view, and to the fact that they assume a nominal Crab-nebula spectral shape, which is flatter than our measurements show. In particular, the LASS and MC detectors both respond to lower energies than *Uhuru* and *Ariel 5* and will tend to overestimate the flux from such a soft spectrum as measured by *EXOSAT*.

The MC experiment did not detect a source at the 4U position in the normal scanning data. In a pointed observation on 1978 May 31, the source was detected at 3.2 σ significance in the 0.9–5.4 keV range of the 2′ FWHM collimator, shown as the multiple parallel lines "A-3" in Figure 1. The equivalent flux was $4.3 \pm 1.9 \times 10^{-11}$ ergs cm^{-2} s^{-1}. Subsequent analysis of scanning data for a source coincident with PKS 2354−35 also gave a significant detection in the 2′ collimator. Figure 2 shows that one of the multiple, 2′ FWHM lines of position includes the galaxy associated with the radio source PKS 2354−35. We measured the center of this galaxy to be at R.A., Decl. (1950) = $23^h54^m25\overset{s}{.}6$, $-35°2'13\overset{''}{.}6$, to $\sim 2''$ rms precision (with perhaps 5″ uncertainty in defining the galaxy center). Schwartz et al. (1979) made a preliminary report of this identification. Failure to obtain a significant detection in the 30″ FWHM MC detector is consistent with demodulation by the finite size of the X-ray source. The *EXOSAT* and *Einstein* imaging detections discussed below provide the unequivocal identification (IPC contours are shown in Fig. 2); however, the importance of the MC result is to prove that the source seen at lower X-ray energies by the imaging telescopes is the same as the hard X-ray source discovered in the sky surveys.

To further study the X-ray properties, we proposed observations using *EXOSAT*, which were carried out with a duration of 18.6 ks, on 1984 December 3. Preliminary results of this were reported by Schwartz et al. (1986). The channel multiplier array (CMA) on the low-energy telescope imaged an extended source, centered on R.A. = $23^h54^m28\overset{s}{.}9$, Decl. = $-35°2'11\overset{''}{.}7$ to $\sim 18''$ positional accuracy. An *Einstein* IPC observation of the quasar 2357−348 (Tananbaum et al. 1979, who reported 2×10^{-13} ergs cm^{-2} s^{-1} as the quasar flux) includes this cluster overlapping the edge of the masked field of view. An extended X-ray source clearly covers the position of PKS 2354−35 (Fig. 2).

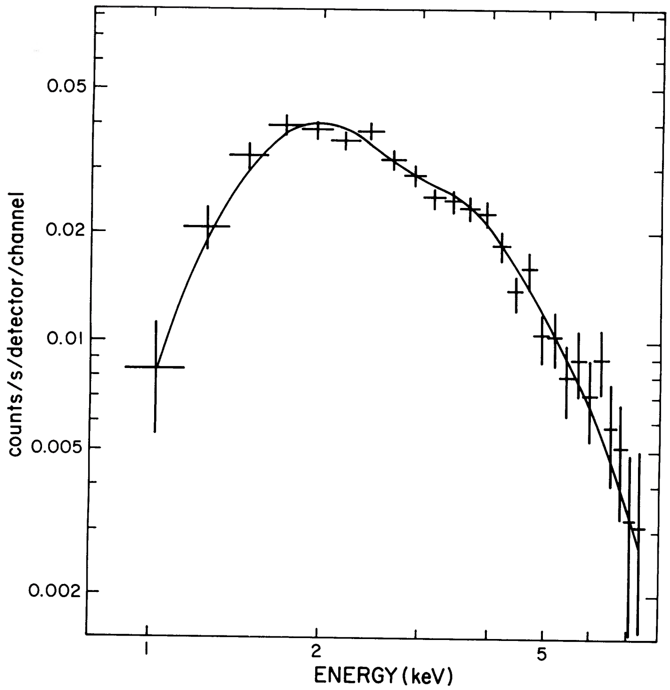

FIG. 3.—*EXOSAT* ME (medium energy detector) net spectrum, plotted as counts per second, per energy bin, per detector vs. energy. The solid line is the predicted counting rate spectrum from the best-fit thermal model, $kT = 3.7$ keV. The 2 σ excess at 6.4 keV is consistent with 6.7 keV-line emission, redshifted from $z = 0.048$.

1.3. *X-Ray Spectrum*

Figure 3 shows the spectral data measured by the *EXOSAT* medium energy proportional counters (ME). The observation was done with half the ME detectors offset from the source and switched nominally halfway through the observation. The offset detectors, appropriately normalized, were used for the background subtraction so that the net spectrum includes counts from each detector "half" minus the other half. In the 12,000 s used in this compilation, significant counts were detected up to 7 keV. The solid line shows the predicted counts for the temperature $kT = 3.7 \pm 0.7$, giving the minimum value of χ^2. (All errors quoted are 90% confidence for the appropriate number of interesting parameters [see Avni 1976], unless stated otherwise.) At 6.4 keV is an indication, at 2 σ excess, for iron line emission redshifted from 6.7 keV in the source frame. This is consistent with the optical redshift, discussed below. Since it would be surprising if Fe emission were totally absent, we will treat this as a detection with the poorly determined equivalent width $1^{+1}_{-\frac{1}{2}}$ keV. For a 3.7 keV plasma ($T = 4.3 \times 10^7$ K), an Fe abundance in the range 0%–160% of cosmic is allowed (see Fig. 1, Bahcall & Sarazin 1978). The minimum χ^2 value is 19.1 for 23 degrees of freedom, without the spectral line. A power-law spectrum with energy index 1.44 ± 0.40 is also allowed and gives a slightly smaller $\chi^2 = 17.0$. Both spectral shapes are consistent with low-energy absorption by neutral hydrogen in our galaxy at the value $N_H = 1.5 \times 10^{20}$ cm^{-2} as given by the 21 cm measurements of Stark et al. (1991). The measured flux inferred for either spectral shape is 1.6×10^{-11} ergs cm^{-2} s^{-1}, 2–6 keV. This flux is a lower bound since the structure of the cluster extends beyond the 3′ plateau in the ME angular response. The corresponding luminosity in this band is 1.6×10^{44} ergs s^{-1}.

1.4. *X-Ray Structure*

The *EXOSAT* telescope CMA detector clearly shows an extended source image. The relatively low quantum efficiency of the CMA does not give good contrast for extended objects, so we omit the noisy CMA contours from Figure 2. For the spectrum determined above, the CMA with the thin lexan filter has a median photon energy of $\sim\frac{1}{4}$ keV. The source is extended beyond the 18″ half-power width of the telescope and is asymmetric, with major axis at $163° \pm 5°$. The emission is peaked and centered on PKS 2354−35. The asymmetry is confirmed by the IPC contours, shown in Figure 2. The latter correspond to a median energy of ~ 1 keV. The angular resolution is $\sim 1\overset{\prime}{.}5$, limited by the telescope optics and by the intrinsic IPC resolution at this off-axis angle of 35′. The IPC contours are distorted by the edge of the detector field (we include the regions normally "masked" out in standard processing), and by shadowing from a window support rib.

Figure 4 shows the CMA radial surface brightness profiles, separately for the quadrants centered along the major and along the minor axes of the surface brightness. We fitted the surface brightness $S(\theta)$ at an angle θ arcmin from the center to a hydrostatic, isothermal sphere profile, $S(\theta) \propto [1 + (\theta/\theta_c)^2]^{-3\beta+1/2}$ (see, e.g., Jones & Forman 1984). Because of the relatively poor statistics, we fix the ratio of energy per unit mass in galaxies to energy per unit mass in hot gas as $\beta = 1$. Then omitting the points within $\theta \leq 1'$, we find core radii $7\overset{\prime}{.}3^{+6}_{-2.5}$ and $2\overset{\prime}{.}5 \pm 2'$, respectively for the major and minor axes, where the confidence quoted is 90% for one interesting parameter (see Avni 1976). For the assumed profile with $\beta = 1$, the absolute flux measured in the ME detector gives a central density of $n_0 = 8 \times 10^{-3}$ cm^{-3}, for which the cooling time at $kT = 3.7$ keV is 4.5×10^9 yr. The density is lower limit, and the cooling time an upper limit, since the ME flux is considered a lower bound for reasons stated above. Also, it can be directly seen that the central emission within 1′ (=84 kpc) exceeds the assumed profile by a factor of ~ 2, which requires a density increase by at least $2^{1/2}$.

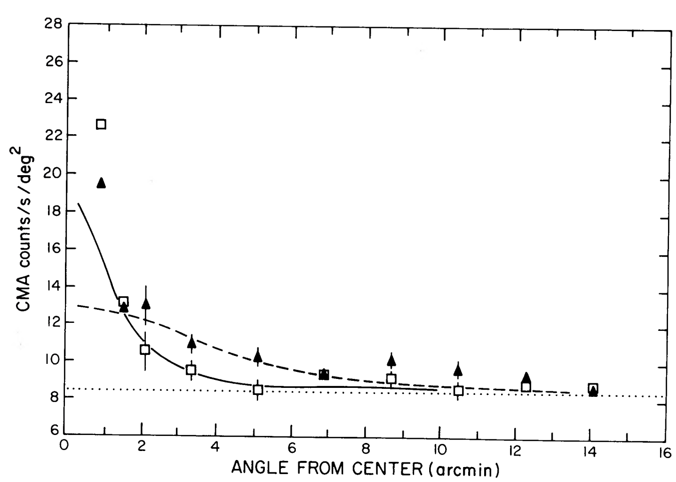

FIG. 4.—For PKS 2354−35 we plot the X-ray counting rate surface brightness from the *EXOSAT* CMA vs. angle from the image center. The squares sum data from the two 90° sectors perpendicular to the X-ray/radio major axis, while the triangles are the two 90° sectors along that axis. The solid curve plots a King profile with a $2\overset{\prime}{.}5$ core, while the dashed line is with a $7\overset{\prime}{.}3$ core. The dotted line is the background estimated from the remainder of the image.

2. OPTICAL OBSERVATIONS

2.1. *Spectrum of the Central Galaxy*

We have obtained a broad-band low-resolution spectrum of the central galaxy in PKS 2354−35 using the 3.9 m Anglo-Australian Telescope (AAT) and the RGO/IPCS spectrograph. A slit of width 4″ and length 30″ was used in conditions of ∼4″ seeing. The resulting spectrum, calibrated against a white dwarf standard, is shown in Figure 5. From the Ca II H and K lines, G band, Mg *b* and Na D features, we derive a redshift of $z = 0.0487 \pm 0.0003$. This result is in agreement with the redshift of $z = 0.048$ reported by Whiteoak (1972), and 0.0486 ± 0.0002 by Green, Godwin, & Peach (1988). We will use $H_0 = 50$ km s^{-1} and $q_0 = 0$ throughout, so the measured redshift corresponds to a luminosity distance of 300 Mpc.

The most notable features are the forbidden [O II] λ3727 and [N II] λ6583 lines. The weaker [N II] λ6548 line is lost in the atmospheric "B" band, and Hα cannot be distinguished between this band and [N II] λ6583. These forbidden lines have been noted as diagnostic of cooling accretion flows (see, e.g., Cowie et al. 1983). These lines are not broadened significantly beyond our system resolution of 12 Å. By deconvolving this resolution we can derive an upper limit intrinsic FWHM less than 900 km s^{-1} for [O II] and less than 500 km s^{-1} for [N II]. The line fluxes are F[O II] = 6.4×10^{-15} ergs cm^{-2} s^{-1} and F[N II] = 15.3×10^{-15} ergs cm^{-2} s^{-1}. The corresponding luminosities, 6.8 and 16.2×10^{40} ergs s^{-1} are lower limits, depending on the spatial extent and symmetry of the emission (see Cowie et al. 1983).

2.2. *Properties of the Cluster*

Carter et al. (1985) have discussed the dynamics of the cluster, including use of unpublished observations by Green (1977). From redshift measurements of 12 cluster members they compute the cluster dispersion velocity $\sigma_c = 894$ km s^{-1} and estimate a cluster core radius of 7′.5, or ∼630 kpc. From a study of the velocity and surface brightness profile of the central galaxy, PKS 2354−35, they derive a core dispersion velocity of $\sigma_g = 300$ km s^{-1} and an effective radius for a de Vaucouleurs surface brightness profile of $R_e = 80''$, or ∼100 kpc. They deduce a mass $M = 4 \times 10^{11}\ M_\odot$ within a 10 kpc radius.

The cluster is listed as 4059 by Abell, Corwin, & Olowin (1989), with richness class 1. Green, Godwin, & Peach (1990) report that the cluster is asymmetric with the long axis at position angles 140°–134°, and that the cD envelope of PKS 2354−35 is at 155° ± 5°.

3. RADIO STRUCTURE OF PKS 2354−35

The radio source PKS 2354−35 was listed by Bolton, Gardner, & Mackey (1964) in the Parkes Catalog and identified with a 15.5 mag galaxy (Bolton, Clarke, & Ekers 1965). It was mapped by the partially completed VLA at 5 GHz, as shown in Figure 6. Although the low declination and irregularly spaced antennae gave the elongated effective beam size as shown, there is clearly an asymmetric double-sided jet structure of 35″ extent. A core component of size <0″.4 at R.A., Decl. (1950) = 23ʰ54ᵐ26ˢ.09, −35°2′16″.7 had a flux of 7 mJy. The position angle between the core and secondary peak is 150°, rotating to ∼170° for the position angle of the outermost contours. Figure 7 shows the radio spectrum of the total source. The GHz spectrum is very steep, $S_\nu \propto \nu^{-1.62}$, characteristic of clusters of galaxies. The total radio luminosity is 1.5×10^{42} ergs s^{-1}, integrated from 10^7 to 10^{11} Hz.

4. DISCUSSION

We have presented the data anticipating our conclusion that the X-ray emission is due to an accretion flow in a cluster of galaxies. Other possibilities which we considered are emission from an active nucleus, or from accretion onto an isolated elliptical galaxy, or an extended corona about such a galaxy.

There is no visible indication of an active nucleus in either the image, or the optical spectroscopy. The optical emission lines are of low excitation and are narrow (<1000 km s^{-1}). The X-ray source is predominantly extended, and with a spectrum steeper than the canonical index of 0.7 found for low-redshift AGNs (see, e.g., Mushotzky 1984). If PKS 2354−35

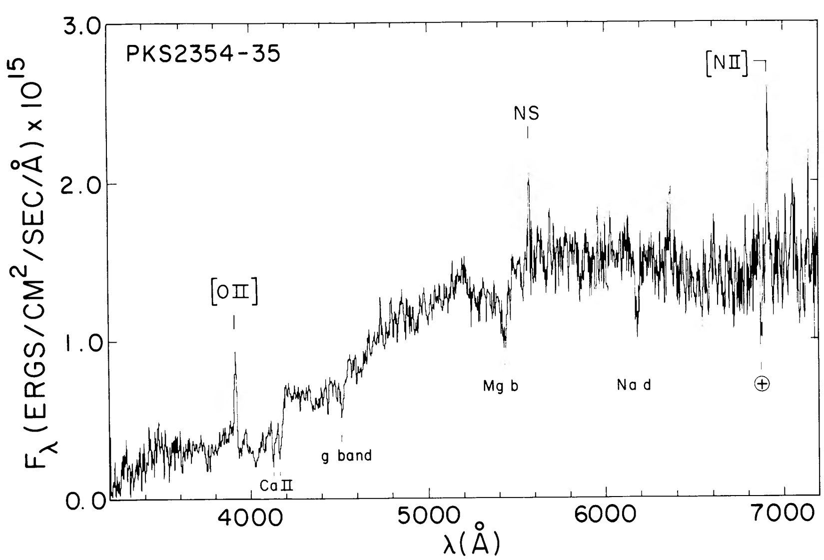

FIG. 5.—Optical spectrum of PKS 2354−35, showing narrow [O II] and [N II] emission lines, and normal galaxy absorption lines of Ca II, *g* band, Mg *b*, and Na *d*.

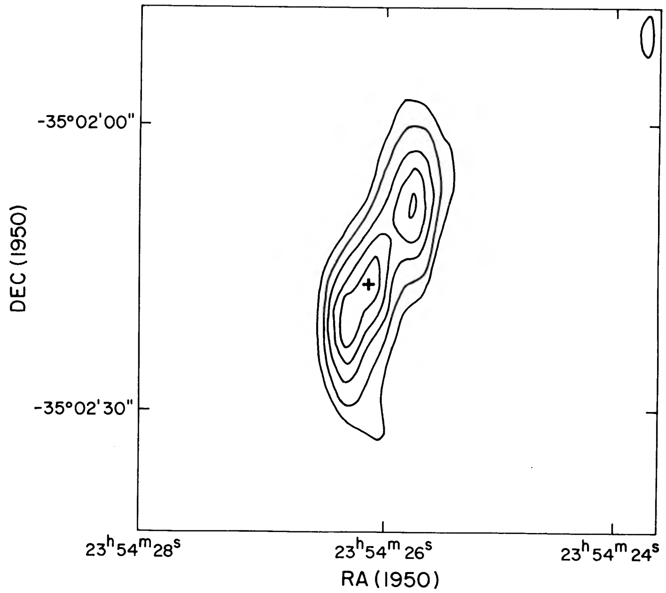

FIG. 6.—Radio map of PKS 2354−35, from the partially completed VLA. The inset at the upper right shows the beam pattern, which is elongated for the southern declination of this source. The plus sign marks a core source of S_{5G} = 7 mJy, and size less than 0″.4. This figure was provided by R. Cameron from the VLA archive.

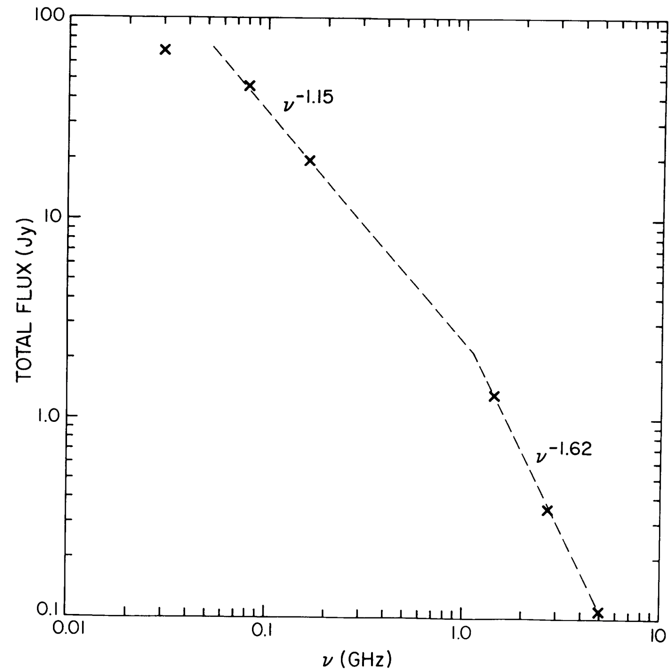

FIG. 7.—Radio spectrum of PKS 2354−35, compiled by R. Cameron from the MSH, PKS, and VLA surveys.

were an isolated "starburst" type galaxy we would expect an X-ray luminosity of only 10^{41} to 10^{42} ergs s^{-1}.

From the optical morphology it is natural to ask if the X-ray emission is associated solely with the galaxy, as observed for M86 and M87 in Virgo (Forman et al. 1979), 3C 264 in A1367 (Jones et al. 1979), and for the isolated elliptical galaxies NGC 3607 (Biermann, Kronberg, & Madore 1982) and NGC 5846 (Biermann & Kronberg 1983). However, the X-ray luminosity of PKS 2354−35 is a factor of 50–1000 higher than the cases noted above. The linear size (200 × 600 kpc core radii) is an order of magnitude greater than for the galaxies imaged by *Einstein* within clusters (above references plus Bechtold et al. 1983). It falls well within the distribution given by Jones & Forman (1984, their Fig. 3) for the XD class of Abell clusters. The X-ray luminosity of PKS 2354−35 is a factor of 200–10^5 greater than the hot coronae reported by Forman, Jones, & Tucker (1985) around E and S0 galaxies. Also, those galaxies were found to be much cooler, with a mean $kT \sim 1$ keV, and a range of temperatures 0.5–1.5 keV (Forman et al. 1985) distinctly below the 3.7 keV found here.

We therefore conclude that the bulk of the X-ray emission is due to the intracluster gas, and the central condensation implies a cooling accretion flow. An estimated accretion rate is given by the approximation $\dot{M} \cong \frac{2}{5}(\mu m/kT)L$ (Fabian et al. 1985). For the bolometric X-ray luminosity $L_x = 4.1 \times 10^{44}$ ergs s^{-1} (extrapolated from the *EXOSAT* 2–6 keV flux assuming a 3.7 keV thermal spectrum), we find $\dot{M} = 320\ M_\odot$ yr^{-1}. In principle, this estimate could be improved by a numerical "unpeeling" of the contribution from outer layers to give a mass flow profile (see Fabian et al. 1980, 1981; Canizares, Steward, & Fabian 1983). In practice, we are limited by modest photon statistics, the absence of spatially resolved spectral information, and in the present case the asymmetry of the spatial profile requires assumptions about the solid geometry of the system (see, e.g., Fabricant, Rybicki, & Gorenstein 1984).

If we assume isotropic velocities of the galaxies, their velocity dispersion is $\sigma = 3^{1/2}\sigma_c$, where $\sigma_c = 894$ is the line of sight measurement by Carter et al. (1985). This gives a ratio of specific energy in galaxies to specific energy in gas of $\beta = \mu m_H \sigma^2/3kT = 1.36 \pm 0.34(1\ \sigma)$. This is consistent with our assumption $\beta = 1$ and possibly with the values $\beta = 0.5$ to 0.8 found by Jones & Forman (1984) to be common for the central dominant galaxy class of X-ray cluster. As noted by Jones and Forman, the true space velocity dispersion, and therefore β, will be lower if the galaxy velocity vectors are biased either intrinsically or by selection of galaxies with radial trajectories through the core (e.g., Abell 1977; Kent & Sargent 1983). If we had fixed $\beta = \frac{2}{3}$ to fit the core radii, we would have derived sizes $\sim$2 times less, strengthening the conclusion of high central density and short lifetime. Clearly, a direct measurement of β from a more precise X-ray profile is required.

PKS 2354−35 ranks among the top dozen cooling flow rates known (see Arnaud 1988). It should be studied for evidence of star formation, filaments, or other traces of mass settling out of the flow. Its X-ray properties are very similar to the system 2A 0335+096 discovered by Schwartz, Schwarz, & Tucker (1980), and for which Romanishin & Hintzen (1988) have found evidence of an Hα bar and possible accretion disk. PKS 2354−35 differs notably in having strong radio emission, and in the coincident, asymmetric radio, X-ray, and cD envelope morphology. Construction of a self-consistent, asymmetric cooling flow model may give insight into the extent to which heating related to the radio source reduces the deduced mass flux (Rosner & Tucker 1989).

We thank R. Cameron for providing the archival VLA plot of PKS 2354−35, and the radio spectrum, which are shown as

Figures 6 and 7. R. R. appreciates the hospitality and assistance of K. Pounds and the University of Leicester X-ray Group, where he performed the initial *EXOSAT* analysis. W. Roberts assisted with the processing of archival *Einstein* IPC data and performed the astrometry reported on PKS 2354−35. We thank H. Tananbaum for comments on the manuscript. This research has been supported, in part, by NASA grant NAGS-493 and NSF grant AST 86-12572 to MIT, by the US/Australia Cooperative Science Program and The Australian Department of Industry, Technology, and Commerce, and by NASA contract NAS 8-30453 and grants NAG8-493 and NAG8-685 to SAO.

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