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ROSAT HRI observations of IRAS P09104 + 4109: a massive cooling flow

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ABSTRACT

A *ROSAT* HRI image of the hyperluminous infrared galaxy IRAS P09104 + 4109 shows extended X-ray emission peaked around the central galaxy in a profile characteristic of a cooling flow. The inferred soft X-ray luminosity is comparable to that detected with *ASCA*. The *ASCA* spectrum is well fitted by a cooling-flow spectrum, indicating a mass cooling rate of about 1000 $M_{\odot}$ yr^{-1}. The cooling flow dominates the total luminosity of the surrounding cluster. Any contribution from a hidden AGN in the host galaxy to either the total *ASCA* spectrum or the HRI image is small.

Key words: galaxies: clusters: general – cooling flows – galaxies: individual: IRAS P09104 + 4109 – X-rays: galaxies.

1 INTRODUCTION

The infrared-luminous galaxy IRAS P09104 + 4109 at redshift $z = 0.442$ (Kleinmann et al. 1988) has recently been shown to be a powerful X-ray source with a rest-frame luminosity in the 2–10 keV band of 2×10^{45} erg s^{-1} (Fabian et al. 1994a; $H_0 = 50$ km s^{-1} Mpc^{-1} is assumed throughout). The optical spectrum has strong, narrow emission lines (Kleinmann et al. 1988) and a highly polarized continuum, indicating that much of the light is scattered (Hines & Wills 1993). The general impression, supported by the detection of a broad Mg II emission line, is that IRAS P09104 + 4109 contains a powerful, obscured, active nucleus (Hine & Wills 1993). The cD host galaxy lies in the centre of a flattened cluster of galaxies (Kleinmann et al. 1988).

The *ASCA* X-ray spectrum of IRAS P09104 + 4109 appeared to support the active nucleus hypothesis, since it is well fitted by a power law of photon index $\Gamma \approx 2$, similar to that of many AGN. In addition, a strong emission line identified as due to helium-like iron was observed. Such a line is expected due to recombination and resonance scattering if the nucleus is hidden and the X-ray continuum scattered into our line of sight by electrons in the cooling intracluster medium within about a kpc from the nucleus (Fabian et al. 1994a). The X-ray emission is consistent, at the resolution of *ASCA* (FWHM ≈ 50 arcsec), with a point source; it is certainly much less extended than the more distant cluster CL 0016 + 16.

In this Letter we report a *ROSAT* High Resolution Imager (HRI) observation of IRAS P09104 + 4109 which resolves the X-ray source spatially and demonstrates that the bulk of the X-ray emission is from the intracluster gas and is not scattered nucleus emission. The X-rays show the highly peaked profile of a massive cooling flow around the host cD galaxy.

2 THE *ROSAT* HRI IMAGE

IRAS P09104 + 4109 was observed with the *ROSAT* HRI for 7937 s on 1994 November 8. An image of the source binned into 1-arcsec pixels is shown in Fig. 1, and a contour map in Fig. 2. If the source were point-like, then 50 per cent of the counts from the source would lie within a radius of 3 arcsec (David et al. 1993). The source is clearly much more extended, with 50 per cent of the counts beyond 14 arcsec. The total extent is difficult to establish, since the signal-to-noise ratio drops rapidly at larger radii; it clearly exceeds several tens of arcsec (Fig. 3). We detect 368 ± 28 counts within a radius of 100 arcsec after correcting for background.

Curiously, the source appears to have a hole at the centre with a bright surrounding ring. The width of the hole, of about 4 arcsec, is consistent with the point response function of the HRI and so it may be real. The aspect-error housekeeping data indicate pointing uncertainties of less than a few arcsec and the hole is apparent in both halves of the data when split in time. It is difficult to estimate the significance of this structure since the real profile of the centre of the source is unknown; we conservatively estimate the significance of the hole to exceed 3σ. The overall position angle and maximum extent of the source as it appears in Fig. 2 are similar to those of the radio source (333° and ~ 12 arcsec from centre

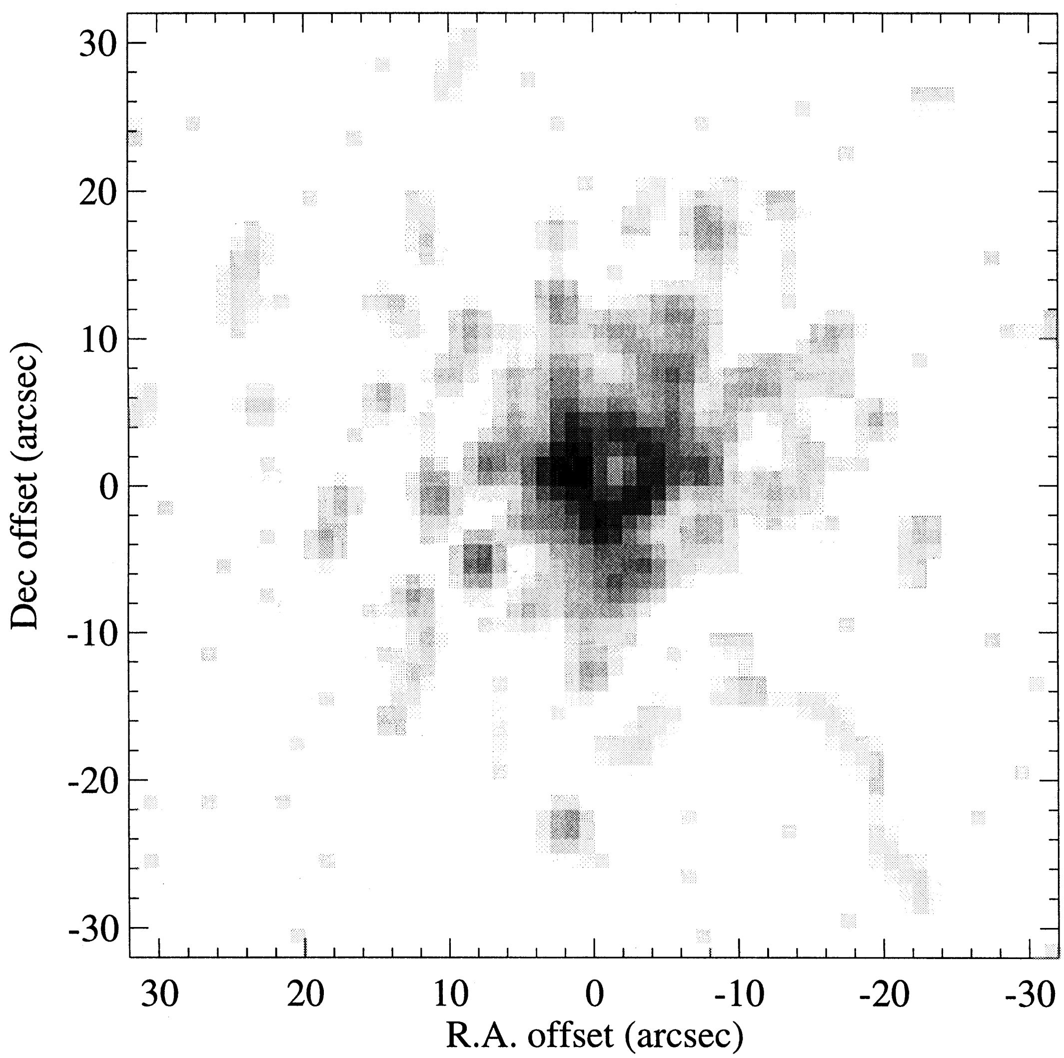

Figure 1. *ROSAT* HRI image of IRAS P09104+4109 binned into 1-arcsec pixels and smoothed with a Gaussian of dispersion 1 arcsec. The centre of the hole is at $09^{\rm h}\,10^{\rm m}\,33\overset{\rm s}{.}06+41°\,08'\,51\overset{''}{.}9$ (J2000); the centre of the radio source (Hines & Wills 1993) lies to the north-west of the hole on the surrounding bright ring.

to lobe: Hines & Wills 1993). We have also examined the second brightest source in the field, which unfortunately only seems to have about 15 counts. These appear confined to a region of size similar to that of the point spread function (PSF) of the HRI, indicating that the HRI image is stable.

The X-ray luminosity of IRAS P09104+4109 in the (observed) 0.1–2 keV *ROSAT* band determined from the HRI count rate is about $(2.9 \pm 0.25) \times 10^{45}$ erg s^{-1}, consistent with that inferred from the *ASCA* spectrum over the observed 0.5–2 keV band and a reasonable spectral extrapolation.

3 DISCUSSION

At least 90 per cent, and (if the central hole in the image is real) probably all, of the X-ray emission detected by *ROSAT* from IRAS P09104+4109 is from an extended source. The very similar X-ray luminosity to that detected with *ASCA* indicates that most of that emission too was from an extended source. Assuming that thermal bremsstrahlung dominates the emissivity, the gas density at ~15-arcsec radius (100 kpc) is ~0.17 cm^{-3}. The cooling time of the gas, $t_{\rm cool}$, assuming from the *ASCA* data a temperature of 11 keV (see below), is ~4×10^9 yr and decreases inward. The peaked X-ray surface brightness profile and short cooling time are characteristic of a massive cooling flow in the host cluster about the central galaxy (for a review of cooling flows see Fabian 1994). The above figures indicate a mass cooling rate of 500 M$_\odot$ yr^{-1} within the inner 100 kpc and ~1000 M$_\odot$ yr^{-1} within the ~200-kpc radius region of the cooling flow where $t_{\rm cool} < 10^{10}$ yr. The surface brightness profile, $S(r)$, of a typical cooling flow cluster varies as $S(r) \propto r^{-1}$ within $r_{\rm cool}$, and roughly as $S(r) \propto r^{-2}$ or steeper at larger radii. We compare a broken power law with the observed profile in Fig. 3. Such steeply peaked X-ray emission is not resolved by *ASCA*. CL 0016+16 has a much flatter X-ray profile with a core radius of 250 kpc (White, Silk & Henry

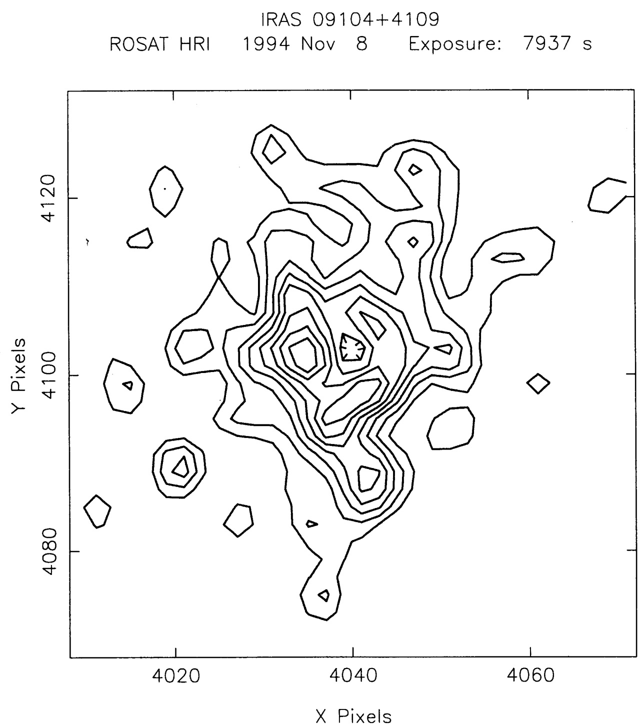

Figure 2. Contour map of the central part of the *ROSAT* HRI image of IRAS P09104+4109 shown in Fig. 1. The units on the axes are raw pixels, each of 0.4 arcsec. The contour levels are at 0.237, 0.355, 0.473, 0.592, 0.710, 0.828. 0.946 and 1.065 count pixel^{-1}.

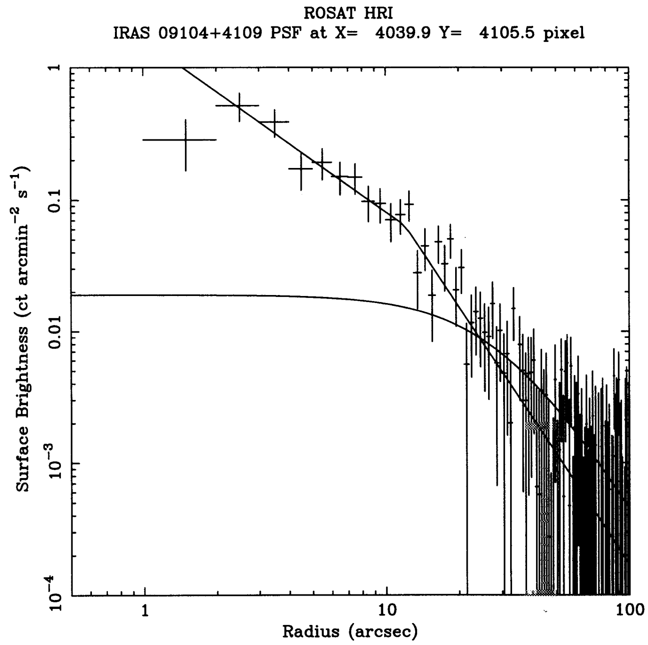

Figure 3. Surface brightness profile of IRAS P09104+4109 after background subtraction. The value inside 1 arcsec is effectively zero. Also shown are the best-fitting models over the range 2–60 arcsec of a broken power law (the break is at 12^{+6}_{-4} arcsec, the slope is 1.3 ± 0.3 at smaller radii and 2.8 ± 0.4 at larger radii) and of a King profile of core radius 30 arcsec and index 1.5.

1981; see Fig. 3 for a comparison of a King model with the IRAS P09104+4109 data) and has no cooling flow. This explains why it is resolved by *ASCA* (Furazawa et al. 1994).

We have refitted the *ASCA* spectra with a model consisting of a cooling flow (see Johnstone et al. 1992) and an isothermal gas (to represent the outer gas). Excess absorption (with 100 per cent covering fraction) is included in the cooling flow component (as found for many nearby cooling flows: White et al. 1991; Allen et al. 1993; Fabian et al. 1994b), and Galactic absorption in both components. We obtain a reasonable fit ($\chi^2 = 571.7$ for 497 bins) for a gas temperature of $11.4^{+\infty}_{-3.2}$ keV, abundance 0.52 ± 0.14 Z$_\odot$, mass cooling rate 1003^{+202}_{-272} M$_\odot$ yr^{-1} and excess column density $2.5^{+1.8}_{-1.1} \times 10^{21}$ cm^{-2} (uncertainties are at the 90 per cent confidence level). The quality of the fit is slightly better than that for the absorbed power law plus line model used previously ($\chi^2 =$ 581: Fabian et al. 1994a). The (rest-frame) 0.5–10 keV luminosity of the source is 2.25×10^{45} erg s^{-1}, with 70 per cent being in the cooling-flow component. This high cooling-flow fraction is a further reason that IRAS P09104+4109 was not resolved by *ASCA*.

We conclude that the *ROSAT* spatially resolved image and the *ASCA* spectrum of IRAS P09104+4109 show that it is surrounded by a massive cooling flow. Indeed, the central hole in the *ROSAT* image could be due to increased excess absorption within the innermost 10 kpc of the flow extinguishing the flux in the soft *ROSAT* band. (The mass of cold absorbing gas must then be $\sim 5 \times 10^{11}$ M$_\odot$.) It is also possible that the narrow optical emission-line nebulosity of the host galaxy is partly due to the cooling flow, since some of its properties such as extent and luminosity (although the gas appears more highly ionized) are similar to those seen in more nearby massive cooling flows (Crawford & Fabian 1992, and references therein).

Alternative interpretations of the central hole are that (i) the radio-emitting plasma from the relatively bright central radio component has either heated or excluded the intracluster gas from that region, as observed in NGC 1275 (Böhringer et al. 1993), or (ii) an outflow or eruption from the central active galactic nucleus (AGN) has excavated that region.

The X-ray appearance of IRAS P09104+4109 bears some striking similarities to that of 3C 295, which is at a similar redshift ($z = 0.46$). Henry & Henriksen (1986) have presented the results of a 103-ks *Einstein Observatory* HRI observation of 3C 295 and concluded that it too lies in a cooling flow. They estimated that the mass cooling rate is only $\dot{M} \sim 145$ M$_\odot$ yr^{-1} by using the peaked luminosity of the inner region and a temperature of about 10^7 K. The gas there is of course cooling from a much higher temperature of ~ 10 keV, so $\dot{M} \sim 1000$ M$_\odot$ yr^{-1} is a more reasonable estimate for 3C 295. We note also that Henry & Henriksen neglected to convolve their King model with the PSF of the instrument, so concluded a minimum core radius for the extended component that was similar in size to the PSF.

Other, similarly large, cooling flows at moderate redshifts are Zw 3146 ($\dot{M} \sim 1000$ M$_\odot$ yr^{-1}, $z = 0.3$: Edge et al. 1994), and A1068 ($\dot{M} \sim 400$ M$_\odot$ yr^{-1}, $z = 0.14$: Allen et al. 1995) which is also infrared-luminous (although 30 times less so than IRAS P09104+4109: Allen 1995). Both of these were found from the *ROSAT* All-Sky Survey (RASS) data (Allen et al. 1992). Distant, cooling-flow-dominated clusters such as

IRAS P09104+4109 may not appear extended in the RASS.

The iron abundance of IRAS P09104+4109 of ~ 0.5 is unusually high for such a high-temperature cluster (see e.g. correlations in Fabian et al. 1994c). An abundance of about half that value would be more typical for nearby clusters of that luminosity. Perhaps the iron abundance was higher at earlier times, as a result, say, of an abundance gradient such as is now seen in the low-temperature Centaurus cluster (Fukazawa et al. 1994). We note, however, that the high-temperature distant cluster A370, which has no large cooling flow, also has a high abundance of 0.5 (Bautz et al. 1994). It remains possible that part of the line in IRAS P09104+4109 is due to resonance scattering and fluorescence of the innermost cooling flow within a kiloparsec of the nucleus, as proposed in our earlier work (Fabian et al. 1994a). The hard continuum can certainly not be electron-scattered by gas at larger radii without the thermal emission from the hot electrons outshining the scattered flux (for a reasonable AGN luminosity comparable to the IR value). The optical depth for resonance scattering is, however, much larger than the Thompson optical depth, and some contribution is likely. Future observations of the iron line at high spatial resolution with *AXAF* are required to separate such components.

IRAS P09104+4109 is the first hyperluminous *IRAS* galaxy to be found in a cooling flow. Part of the infrared and much of the optical line luminosities may be due to the flow, but the detection of broad Mg II emission and strong optical polarization by Hines & Wills (1993) indicates a central AGN. The gas deposited by the flow is an obvious source of fuel for such an AGN, and they may be linked by Compton cooling of the innermost flow, as discussed by Fabian & Crawford (1990). Further work is necessary to unravel the different components of this interesting object.

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