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Limits on the X-ray emission from several hyperluminous *IRAS* galaxies

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ABSTRACT

We report long, pointed *ROSAT* HRI observations of the hyperluminous galaxies IRAS F00235+1024, F12514+1027, F14481+4454 and F14537+1950. Two of them are optically classified as Seyfert-like. No X-ray sources are detected at the positions of any of the objects, with a mean upper limit $L_X/L_{Bol} \simeq 2.3\times10^{-4}$. This indicates that any active nuclei are either atypically weak at X-ray wavelengths or obscured by column densities $N_H > 10^{23}$ cm^{-2}. They differ markedly from 'ordinary' Seyfert 2 galaxies, bearing a closer resemblance in the soft X-ray band to composite Seyfert 2 galaxies or to some types of starburst.

Key words: galaxies: individual: IRAS F00235+1024 – galaxies: individual: F12514+1027 – galaxies: individual: F14481+4454 – galaxies: individual: F14537+1950 – infrared: galaxies – X-rays: galaxies.

1 INTRODUCTION

With bolometric luminosities in excess of $10^{13}L_{\odot}$ emitted mostly in the mid- to far-infrared, hyperluminous *IRAS* galaxies are among the most luminous objects in the Universe. The origin of the high luminosity, however, remains uncertain, with massive starbursts and buried active nuclei having both been implicated as radiation sources capable of powering thermal reradiation by dust grains (see e.g. Rowan-Robinson et al. 1993; Sanders & Mirabel 1996). Morphologically, many of these galaxies display the signatures of recent interaction or merger events, either of which could initiate bursts of star formation or drive gas into the central regions to build/fuel active nuclei (AGN) (Sanders et al. 1988b). The model of Sanders et al. (1988a) describes how, following the collision of two gas-rich spirals, such systems evolve through being *IRAS* galaxies into optically selected QSOs.

A number of hyperluminous galaxies possess Seyfert 2-like optical spectra, with high-ionization emission lines and strongly polarized continua indicative of the presence of buried active nuclei [see e.g. Hines et al. (1995) for IRAS F15307+3252; Hines & Wills (1993) and Kleinmann et al. (1988) for IRAS P09104+4109]. If so, this would make possible a tentative identification of hyperluminous galaxies as the long-sought class of type 2 quasars: Seyfert 2 galaxies with bolometric luminosities characteristic of quasars.

X-ray observations exist for several hyperluminous galaxies and may provide a useful means of discriminating between a starburst and an AGN, since the latter are often prominent at these wavelengths. A source with strong iron K line emission was detected by *ASCA* at the position of IRAS P09104+4109 (Fabian et al. 1994), favouring a model in which the observed X-rays are scattered into our line of sight from a hidden quasar. A subsequent *ROSAT* High Resolution Imager (HRI) image of the same source instead shows that the emission is actually dominated by a cooling flow (Fabian & Crawford 1995), consistent with the observation that that object appears to reside at the core of a rich cluster of galaxies (Kleinmann et al. 1988). The hyperluminous galaxy IRAS F20460+1925 and the ultraluminous galaxy IRAS F23060+0505 are X-ray-detected (Ogasaka et al. 1997 and Brandt et al. 1997, respectively) behind intrinsic column densities of $\sim10^{22}$cm^{-2}. The hyperluminous galaxy IRAS F10214+4724 was only marginally detected in X-rays [Lawrence et al. 1993: its luminosity is now known to be greatly enhanced by gravitational lensing (Eisenhardt et al. 1996)]. A 20-ks HRI observation of IRAS F15307+3252 (Fabian et al. 1996, hereafter F96) failed to detect any X-ray source at an upper limit of $\sim4\times10^{43}$ erg s^{-1}, representing less than 2×10^{-4} of the bolometric luminosity and indicating either that the nucleus emits an anomalously small fraction of its total power in X-rays ($\ll L_X/L_{Bol}\sim 5$ per cent for a typical quasar) or that less than 0.4 per cent of the nuclear X-ray flux is scattered into our line of sight.

The key to an improved understanding of the hyperluminous galaxy phenomenon lies in the study of larger samples. To this end we report *ROSAT* HRI observations of a further four such objects, three of which were identified by Cutri et al. (in preparation) using deep optical/radio imaging of *IRAS* colour-selected 'warm' extragalactic objects; the chosen objects are the most luminous of those recently found by this method and have redshifts substantially below that of IRAS F15307+3252, thus enhancing their detectability. Two of these sources, IRAS F12514+1027 and F14481+4454, have optical spectra similar to Seyfert 2 galaxies, indicating at least the presence of an active nucleus. The third object, IRAS F14537+1950, exhibits starburst characteristics in its optical spectrum. The fourth object in our sample, IRAS F00235+1024, was discovered by McMahon et al. (in preparation) during a systematic search for ultraluminous *IRAS* galaxies with the

Table 1. Summary of the properties of the four hyperluminous *IRAS* galaxies and the results of our analysis of the *ROSAT* HRI data.

IRAS	F00235+1024	F12514+1027	F14481+4454	F14537+1950
z	0.575‡	0.30†	0.66†	0.64†
optical classification:	starburst	Seyfert 2	Seyfert 2	starburst
Galactic column density N_H : 10^{20} cm^{-2}	5.1	1.73	1.72	2.81
observation dates:	1995 December 1 1996 July 2	1996 July 11–14 1997 June 16	1996 December 25 1997 July 14	1996 August 9–12
exposure time: s	60365	20398	26883	17970
count rate: 10^{-4} count s^{-1}	< 0.70	< 2.40	< 1.72	< 1.99
$\Im$: 10^{-14} erg cm^{-2} s^{-1}	< 0.50	< 1.21	< 0.87	< 1.17
L_X : 10^{43} erg s^{-1}	< 0.87	< 0.54	< 2.07	< 2.61
L_{Bol} : 10^{13} $L_\odot$	1.5‡	1.0†	2.0†	2.0†
L_X/L_{Bol}	$< 1.5 \times 10^{-4}$	$< 1.4 \times 10^{-4}$	$< 2.7 \times 10^{-4}$	$< 3.4 \times 10^{-4}$
ΔN_H : 10^{23} cm^{-2}	1.8	1.0	1.5	1.5
$A_V^\star$: mag	120	67	100	100
L_{SX}/L_{Bol}	$< 8.96 \times 10^{-5}$	$< 7.81 \times 10^{-5}$	$< 2.09 \times 10^{-4}$	$< 2.41 \times 10^{-4}$

† From Cutri et al. (in preparation); ‡ from McMahon et al. (in preparation).
⋆ Using the N_H:$E(B-V)$ conversion of Bohlin, Savage & Drake (1978), with a dust/gas ratio equal to that of the Galaxy.

Cambridge APM machine; its optical spectrum was subsequently found to be starburst-like. When plotted on the *IRAS* colour diagram of Rowan-Robinson & Crawford (1989), IRAS F12514+1027 F14481+4454 fall within the region occupied by the Seyfert galaxies (galaxies with infrared spectra dominated by starburst or disc components lie elsewhere in the diagram). The other two objects in our sample cannot be placed on the diagram, since their *IRAS* photometric data are of poorer quality.

2 *ROSAT* HRI OBSERVATIONS

IRAS F00235+1024, F12514+1027, F14481+4454 and F14537+1950 were observed with the *ROSAT* (Trümper 1983) HRI (David et al. 1995) between the dates given in Table 1. No sources are detected at the optical positions of the objects. Upper limits on the count rates (calculated at the 90 per cent confidence level using the Bayesian method of Kraft, Burrows & Nousek 1991) are shown in Table 1. Also shown are upper limits on the unabsorbed flux, $\Im$, and luminosity, L_X, for each object in the intrinsic 0.1–2.4 keV band, assuming a power-law continuum of photon index 2. For comparison with a sample of starburst galaxies in Section 3.2, a thermal bremsstrahlung source spectrum with $kT = 1$ keV was used to calculate L_{SX}, the luminosity in the intrinsic 0.5–2.0 keV band. Allowance was made for photoelectric absorption by the Galaxy (with column densities N_H shown in the table), and a cosmology of $H_0 = 50$ km s^{-1} Mpc^{-1} and $q_0 = 0.5$ has been adopted throughout.

3 DISCUSSION

3.1 On active nuclei

From the table, we see that the upper limits on the ratio L_X/L_{Bol} are quite similar for all of the objects, with a mean of $\simeq 2.3 \times 10^{-4}$. If we adopt in the first instance the assumption that the sources are powered by active nuclei, we can use this figure to make a number of inferences about their properties. A similar discussion was given in F96 for the case of IRAS F15307+3252 which was observed to have $L_X/L_{Bol} < 2 \times 10^{-4}$ (a 3σ upper limit). We show, in Fig. 1, L_X/L_{Bol} plotted against L_{Bol} for these sources and some representative AGN and starbursts. Denoted by the arrows in this figure are the upper and lower ends of the range of values of L_X/L_{IR} for the sample of Seyfert 2 galaxies in Green, Anderson & Ward (1992). The latter authors provide *Einstein* Imaging Proportional Counter (IPC) (0.5–4.5 keV) X-ray luminosities corrected for Galactic absorption which we convert to (0.1–2.4 keV) luminosities (L_X). Luminosities in the 8–1000 μm band (L_{IR}) were calculated from the *IRAS* photometric data in Bonatto & Pastoriza (1997) according to the prescription of Perault (1987). In our sample we include only those

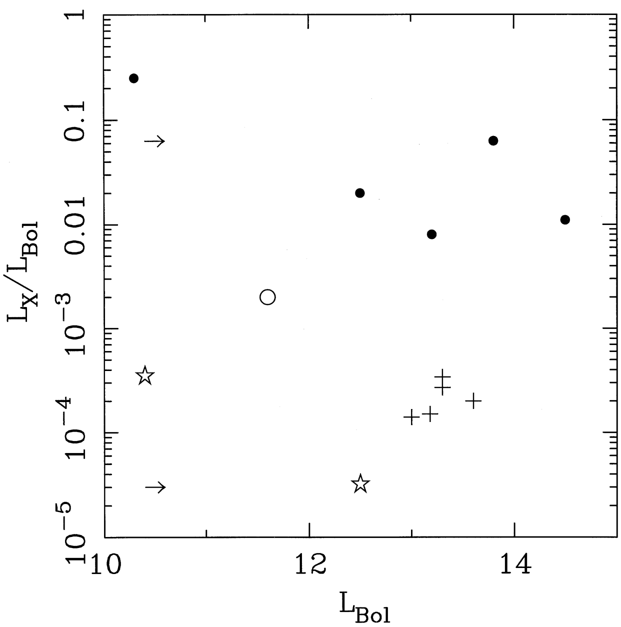

Figure 1. L_X/L_{Bol} plotted against L_{Bol}. The filled circles represent known AGN, from MCG–6-30-15 on the left from Reynolds et al. (1997), through IRAS F23060+0505 (Brandt et al. 1997) and F20460+1925 (Ogasaka et al. 1997) in the centre, to PG 1634+706 and 1718+481 (Nandra et al. 1995) on the right. The crosses are the 90 per cent confidence level upper limits from the present data together with IRAS F15307+3252 (F96). The open circle is the Seyfert 2 galaxy NGC 1068 (Wilson et al. 1992), and the star symbols are (left to right) the starburst galaxies M82 (Kii et al. 1997) and Arp 220 (Kii et al. 1997). The arrows denote (for arbitrary L_{Bol}) the upper and lower ends of the range for a sample of Seyfert 2 galaxies (see text for details). L_X for all objects has been corrected to an assumed 0.1–2.4 keV intrinsic power-law spectrum with a photon index of 2.

Seyfert 2 galaxies that were detected in all four *IRAS* bands and with the *Einstein* IPC. We note that for Seyfert 2 galaxies L_{IR} may differ substantially from L_{Bol}, but we have insufficient information upon which to base a computation of the latter quantity. Nevertheless, since $L_{IR} \simeq L_{Bol}$ for the hyperluminous galaxies, the comparison is still a useful one. The large extent of the range for the Seyfert 2 galaxies is, we believe, a consequence of the heterogeneous nature of the sample, comprising composite objects with active nuclei and starbursts, as well as 'ordinary' Seyfert 2 galaxies without the latter component. (We are not aware of any study that compares the values of L_X/L_{Bol} for the known Seyfert 2 sub-populations.)

If being observed directly, it follows that the active nuclei are emitting less than 0.02 per cent of their power at soft X-ray wavelengths, which is substantially below the figure of 5 per cent for a typical quasar (F96). Assuming that any active nuclei are intrinsically typical, the existence of material with absorbent or scattering properties is thus inferred. In the former case, i.e. if nuclei are being observed in direct light, quantities of material capable of depressing the soft X-ray fluxes by minimum factors of between $\simeq$150 (for IRAS F14537+1950) and $\simeq$360 (for IRAS F12514+1027) are required. A proper treatment of redshifted absorption using XSPEC (assuming an intrinsic power-law continuum with a photon index of 2) demonstrated that this can be effected by intrinsic column densities $\Delta N_H > 10^{23}$cm^{-2} (the inferred ΔN_H for each object, along with the corresponding value of the visual extinction A_V, is shown in the table). This is very much less than the $\Delta N_H \sim 1.5 \times 10^{24}$cm^{-2} at which the sources would become optically thick to Compton scattering.

Alternatively, if the intrinsic column densities are large enough to block all of the direct light, the results imply that on average less than 0.5 per cent of the soft X-ray flux is scattered into our line of sight (assuming a typical intrinsic value of 5 per cent for L_X/L_{Bol}; if the spread in the latter quantity is incorporated – see Fig. 1 – the scattering fraction can be as high as $\sim$3 per cent). This is surprisingly small [cf. the $\simeq$ 10 per cent scattering fraction inferred in the optical for IRAS F15307+3252 by Hines et al. (1995)] and implies that any optical scattering medium is composed of dust (which does not scatter X-rays through large angles), not electrons. The hyperluminous galaxies are in this way different from nearby, lower luminosity Seyfert 2 galaxies such as NGC 1068 where electron scattering plays an important role. Note too from Fig. 1 that they have a significantly lower value of L_X/L_{Bol} than that of NGC 1068, which is itself low for a (non-composite) Seyfert galaxy (see e.g. Awaki, Ueno & Koyama 1997). This is perhaps an indication that even any scattered soft X-ray emission in our objects is absorbed.

It could instead be that intrinsically typical active nuclei are present but that they account for less than 5 per cent of the total bolometric flux from the objects (assuming a scattering fraction of 10 per cent). They may therefore be high-luminosity counterparts to composite starburst/Seyfert 2 galaxies, which, according to Ueno et al. (1997), fall toward the lower end of the Seyfert 2 range in Fig. 1, near the region occupied by our upper limits. Based upon the appearance of the optical spectrum, however, F96 provide reasons for believing this scenario to be unlikely for IRAS F15307+3252.

Indeed, given the large amounts of gas expected to be driven to the nucleus of the galaxy during a merger, and discoveries at low redshift that most galaxies have central black holes (Magorrian et al. 1998), it would be surprising if there were no luminous AGN in the objects observed. The Eddington limit does, however, provide a restriction on the AGN luminosity component, and requires a central mass exceeding $3-6 \times 10^8$ M$_\odot$ in order that the AGN component dominates a bolometric luminosity of $L_{Edd} = 1-2 \times 10^{13}$ L$_\odot$. If the merging galaxies had black holes with masses ranging between that of our Galaxy (2.6×10^6 M$_\odot$: Eckart & Genzel 1997) and M31 (6×10^7 M$_\odot$: Magorrian et al. 1998), they could not then power the hyperluminous *IRAS* galaxies at the observed rate. In other words, a merger between our Galaxy and M31 could not produce a hyperluminous AGN. (The Salpeter black hole growth time-scale exceeds the likely age of any merger.) A hyperluminous AGN requires a supermassive black hole in the first place.

3.2 On starbursts

IRAS F00235+1024 and F14537+1950 are classified as starbursts on the basis of optical spectra (McMahon et al. in preparation and Cutri et al. in preparation, respectively). In order to assess the implications of the present soft X-ray data for a starburst interpretation for these objects, we compare our upper limits on the quantity L_{SX}/L_{Bol} with the range of values given by Kii et al. (1997) for a sample of starburst galaxies. Our definition of L_{SX} is motivated by the latter authors' use of the soft X-ray *ASCA* band of 0.5−2.0 keV and by the fact that the spectra of starburst galaxies are best described by thermal models. Kii et al. report that L_{SX}/L_{Bol} is of the order of 10^{-4} for starburst galaxies, ranging from 3.2×10^{-5} for Arp 220 [an ultraluminous starburst galaxy the *ASCA* spectrum of which is analysed by Iwasawa & Fabian (in preparation)] to 3.2×10^{-4} for M82. It can be seen from Table 1 that the 90 per cent upper limits for the objects in our sample fall within this range and are thus not wholly inconsistent with a starburst origin for the soft X-ray emission. Our data suggest that, if starbursts do exist in these objects, they are more likely to resemble that in Arp 220 than that in M82.

4 CONCLUSIONS

We have reported the non-detection at soft X-ray wavelengths of four hyperluminous galaxies. This result extends to a larger sample that found by F96 for IRAS F15307+3252, thus enabling constraints to be placed upon the properties of some of the most luminous objects in the Universe.

Two of the objects show evidence for an active nucleus in their optical spectra. These AGN must be either anomalously weak at X-ray wavelengths or obscured by column densities $N_H > 10^{23}$ cm^{-2}. Any optical scattering medium must be composed of dust, not electrons. The upper limits fall near the lower end of the range for a sample of Seyfert 2 galaxies, close to the region where objects of the latter type are thought to be of a composite nature (possessing starburst and active nucleus components).

By comparison with *ASCA* observations of the soft X-ray fluxes from a sample of local starburst galaxies, we find that our *ROSAT* observations are not inconsistent with the presence of starbursts in our objects. For IRAS F00235+1024 and F14537+1950, this is at least in line with expectations based upon the appearance of their optical spectra.

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REFERENCES

Awaki H., Ueno S., Koyama K., 1997, in Makino F., Mitsuda K., eds, X-ray Imaging and Spectroscopy of Cosmic Hot Plasmas. Universal Academy Press, Tokyo, p. 271
Bohlin R. C., Savage B. D., Drake J. F., 1978, ApJ, 224, 132
Bonatto C. J., Pastoriza M. G., 1997, ApJ, 486, 132
Brandt W. N., Fabian A. C., Takahashi K., Fujimoto R., Yamashita A., Inoue H., Ogasaka Y., 1997, MNRAS, 290, 617
Cutri R. M., Huchra J. P., Low F. J., Brown R. L., Vanden Bout P. A., 1994, ApJ, 424, L65
David L. P., Harnden F. R., Kearns K. E., Zombeck M. V., 1995, The *ROSAT* High Resolution Imager. GSFC, Greenbelt, MD
Eckart A., Genzel R., 1997, A&AS, 191, 9707E
Eisenhardt P. R., Armus L., Hogg D. W., Soifer B. T., Neugebauer G., Werner M. Q., 1996, ApJ, 461, 72
Fabian A. C., Crawford C. S., 1995, MNRAS, 274, L63
Fabian A. C. et al., 1994, ApJ, 436, L51
Fabian A. C., Cutri R. M., Smith H. E., Crawford C. S., Brandt W. N., 1996, MNRAS, 283, L95 (F96)
Green P. J., Anderson S. F., Ward M. J., 1992, MNRAS, 254, 30
Hines D. C., Wills B. J., 1993, ApJ, 415, 82
Hines D. C., Schmidt G. D., Smith P. S., Cutri R. M., Low F. J., 1995, ApJ, 450, L1
Kii T., Nakagawa T., Fujimoto R., Ogasaka T., Miyazaki T., Kawabe R., Terashima Y., 1997, in Makino F., Mitsuda K., eds, X-ray Imaging and Spectroscopy of Cosmic Hot Plasmas. Universal Academy Press, Tokyo
Kleinmann S. G., Hamilton D., Keel W. C., Wynn-Williams C. G., Eales S. A., Becklin E. E., Kuntz K. D., 1988, ApJ, 328, 161
Kraft R. P., Burrows D. N., Nousek J. A., 1991, ApJ, 374, 344
Lawrence A. et al., 1993, MNRAS, 260, 28
Magorrian J. et al., 1998, AJ, 115, 2285
Nandra K., Fabian A. C., Brandt W. N., Kunieda H., Matsuoka M., Mihara T., Ogasaka Y., Terashima Y., 1995, MNRAS, 276, 1
Ogasaka Y., Inoue H., Brandt W. N., Fabian A. C., Kii T., Nakagawa T., Fujimoto R., Otani C., 1997, PASJ, 49, 179
Perault M., 1987, PhD thesis, Univ. Paris
Reynolds C. S., Ward M. J., Fabian A. C., Celotti A., 1997, MNRAS, 291, 403
Rowan-Robinson M., Crawford J., 1989, MNRAS, 283, 523
Rowan-Robinson M. et al., 1993, MNRAS, 261, 513
Sanders D. B., Mirabel I. F., 1996, ARA&A, 34, 749
Sanders D. B., Soifer B. T., Elias J. H., Madore B. F., Matthews K., Neugebauer G., Scoville N. Z., 1988a, ApJ, 325, 74
Sanders D. B., Soifer B. T., Elias J. H., Neugebauer G., Matthews K., 1988b, ApJ, 328, L35
Trümper J., 1983, Adv. Space Res., 4, 241
Ueno S., Awaki H., Hayashi I., Koyama K., 1997, in X-ray Imaging and Spectroscopy of Cosmic Hot Plasmas. Universal Academy Press, Tokyo
Wilson A. S., Elvis M., Lawrence A., Bland-Hawthorn J., 1992, ApJ, 391, L75

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