A hard X-ray constraint on the presence of an AGN in the ultra-luminous infrared galaxy Arp220

K. Iwasawa¹, G. Matt², M. Guainazzi³ and A.C. Fabian¹

¹Institute of Astronomy, Madingley Road, Cambridge CB3 0HA
²Dipartimento di Fisica, Universita degli Studi Roma Tre, Via della Vasca Navale 84, I-00146 Roma, Italy
³XMM-Newton SOC, VILSPA, ESA, Apartado 50727, 28080 Madrid, Spain

ABSTRACT
We present X-ray results on the ultraluminous infrared galaxy Arp220 obtained with BeppoSAX. The X-ray emission up to 10 keV is detected. No significant signal is detected with the PDS detector in the higher energy band. The 2–10 keV emission has a flat spectrum ($\Gamma \sim 1.7$), similar to M82, and a luminosity of $\sim 1 \times 10^{43}$ erg s$^{-1}$. A population of X-ray binaries may be a major source of this X-ray emission. The upper limit of an iron K line equivalent width at 6.4 keV is $\sim 600$ eV. This observation imposes so far the tightest constraint on an active nucleus if present in Arp 220. We find that a column density of X-ray absorption must exceed $10^{25}$ cm$^{-2}$ for an obscured active nucleus to be significant in the energetics, and the covering factor of the absorption should be almost unity. The underluminous soft X-ray starburst emission may need a good explanation, if the bolometric luminosity is primarily powered by a starburst.

Key words: Galaxies: individual: Arp220 — X-rays: galaxies

1 INTRODUCTION

With an 8–1000µm luminosity of $L_{ir} \simeq 1.2 \times 10^{12} L_{\odot}$, Arp220 is one of the nearest ultra-luminous infrared galaxies (ULIGs) discovered by IRAS (Soifer et al 1987; we adopt a distance of 73 Mpc for Arp220 throughout). Since Arp220 is often regarded as a nearby template for dusty galaxies at high redshift undergoing a vigorous star formation (e.g., faint SCUBA sources), it is important to identify its power source. The general consensus since ISO observations (Sturm et al 1996; Genzel et al 1998) has been massive young stars. However, some infrared luminous galaxies like NGC4945 and NGC6240, which apparently show no outward evidence for an active galactic nucleus (AGN) even in ISO observations, have turned out to contain a heavily obscured AGN visible only in the hard X-ray band (e.g., Iwasawa et al 1993; Done et al 1996; Vignati et al 1999). The soft X-ray data of Arp220 taken by the ROSAT PSPC and HRI show extended emission similar in shape to the H$\alpha$ nebula. This can be well explained by starburst-driven winds (Heckman et al 1996). The soft X-ray luminosity of $\sim 5 \times 10^{46}$ erg s$^{-1}$, however, appears to be small relative to the large infrared luminosity, when compared with other starburst galaxies. This raises concern with regard to the intensity of starburst (Iwasawa 1999).

The previous hard X-ray limits on Arp220 by HEAO-1 (Rieke 1988), CGRO/OSSE (Dermer et al 1997) and Ginga ruled out a bright hard X-ray source ($> 10^{-11}$ erg cm$^{-2}$ s$^{-1}$). A short ASCA observation also indicates no evidence for an active nucleus (Iwasawa 1999). The only possibility for an energetically significant active nucleus to exist in Arp220 would be in the form of a “Compton-thick source”: no detection of transmitted light in the ASCA bandpass ($\leq 10$ keV) means that a central source must be absorbed by a column density in excess of $2 \times 10^{24}$ cm$^{-2}$. Such an X-ray source could be detected above 10 keV, provided that the column density is not so large, that all the transmitted X-ray flux is highly reduced. Although faint reflected/scattered light may exist, it should be very faint, given the ASCA constraint on the 5–10 keV emission. A large X-ray telescope such as Chandra and XMM-Newton is needed to investigate it. The main aim of our BeppoSAX observation is to search for a hard X-ray source above 10 keV with the PDS detector. Since the ASCA result indicates that a reflection component alone, if at all present, should be below the PDS sensitivity limit, any detection with the PDS would therefore be due to radiation transmitted through a column density of a few times $10^{24}$ cm$^{-2}$.

2 OBSERVATION AND DATA REDUCTION

Arp220 was observed with the NFI instruments (LECS, MECS and PDS) onboard BeppoSAX (Boella et al 1997)
the relatively broad point spread function of the LECS and MECS, cross contamination between Arp220 and the southern source is unavoidable. We therefore collected spectral data from a region containing both Arp220 and the southern source (a circular region of a radius of 3 arcmin for the MECS and 4 arcmin for the LECS, respectively), and then corrected for the southern source contribution by utilizing the similarity in spectral shape and flux in the 0.5–2 keV band between the two sources (see Iwasawa 1999; this spectral similarity is only valid for a low spectral resolution detector such as the ROSAT PSPC and a detailed analysis of the ASCA SIS data does show some difference in temperature and metallicity between the two sources), which should suffice for the present quality of data. Above 4 keV, contamination from the southern source is negligible. The spectrum presented in Fig. 1 contains the southern source but the flux and luminosity of Arp220 quoted in this paper have been corrected for the contamination.

A power-law fit to the 2–10 keV MECS data gives \( \Gamma = 1.70^{+0.35}_{-0.46} \) when Galactic absorption \( (N_H = 4 \times 10^{20} \text{cm}^{-2}) \) is assumed. The spectral slope of Arp220 should be slightly harder, since the data contains some contribution from the southern source up to 4 keV. The thermal emission model requires a temperature higher than 4.5 keV (the best-fit value is about 10 keV).

Extrapolating the power-law to lower energies leaves surplus soft X-ray emission below 2 keV, which can be attributed to thermal emission from the extended gas. Although actual X-ray emission from a starburst galaxy is probably more complex than a single temperature plasma (e.g., Dahlem et al 2000), the present quality of the data is insufficient to decompose multiple components. The LECS and MECS data were fitted with an absorbed power-law plus the MEKAL thermal emission model with Solar abundance, modified only by Galactic absorption. The temperature of the thermal emission model obtained is \( kT = 0.53^{+0.37}_{-0.22} \) keV. The absorption column density for the power-law is \( N_H = 2^{+4}_{-2} \times 10^{21} \text{cm}^{-2} \), when a photon index of \( \Gamma = 1.8 \) is assumed. The \( \chi^2 \) value of this fit is 56.4 for 45 degrees of freedom.

As a Fe-L bump around 1 keV is evident, metallicity of the gas is not unusually low, as suggested by the fit to the ROSAT PSPC data by Read & Ponman (1998). This is also true for the ASCA SIS spectrum taken only from the Arp220 region. As far as reasonable metallicity \( (Z \geq 0.1 Z_\odot) \) is assumed for the MEKAL model, no excess absorption above Galactic value is required.

No emission line feature is clearly detected in the spectrum in the energy band above 2 keV; the excess around 6 keV is not statistically significant. The 90 per cent upper limit of a narrow line flux at 6.4 keV in the galaxy-frame is \( 1.1 \times 10^{-6} \text{ph s}^{-1} \text{cm}^{-2} \), corresponding to the equivalent width of 600 eV.

The observed fluxes of Arp220 in the 0.5–2 keV and 2–10 keV bands are \( 8 \times 10^{-14} \text{erg cm}^{-2} \text{s}^{-1} \) and \( 1.8 \times 10^{-13} \text{erg cm}^{-2} \text{s}^{-1} \), respectively. These values are consistent with the ASCA measurements (Iwasawa 1999). The corresponding luminosities for our assumed distance are \( 5 \times 10^{44} \text{erg s}^{-1} \) in the 0.5–2 keV band and \( 1.1 \times 10^{45} \text{erg s}^{-1} \) in the 2–10 keV band. The uncertainty in the soft X-ray flux induced by the contamination from the southern source is about 30 per cent at most.

© 0000 RAS, MNRAS 000, 000–000

**Figure 1.** The BeppoSAX spectrum of Arp220 obtained from the LECS, MECS and PDS. The two observations have been integrated to produce this spectrum. The histogram shows the best-fit model consisting of an absorbed power-law \( (\Gamma = 1.8) \) and the MEKAL thermal emission model. The 13–50 keV PDS data point is consistent with the systematic error of the detector and regarded as an upper limit. The extrapolation of the best-fit model for the LECS and MECS data is indicated by the dotted line.
4 INTERPRETATION

4.1 X-ray emission below 10 keV

The X-ray spectrum of Arp220 below 10 keV can be described by a combination of sub-keV thermal emission and a moderately absorbed power-law, as suggested by Iwasawa (1999) based on the ASCA observation. The soft X-ray emission is explained well with thermal emission from the interstellar medium (ISM) heated by a Galactic-scale outflow, probably driven by a starburst (Heckman et al 1996).

Although the origin of the 2–10 keV emission tail is unclear, we suggest a population of X-ray binaries as a good candidate. As shown in Fig. 2, the 2–10 keV spectra of Arp220 and M82 are very similar. ASCA monitoring observations of M82 showed a significant X-ray variability in the 2–10 keV band (Ptak & Griffiths 1998; Matsumoto & Tsuru 1999). A recent Chandra HRC observation revealed that there are many discrete sources in the galaxy as well as underlying diffuse hot gas, and the brightest off-nuclear source is highly variable (e.g., Matsumoto et al 2001). Combining these results, much of the hard X-ray tail in M82 is likely to be due to a collection of discrete sources, the majority of which are probably black hole binaries. A similar picture is also suggested for another nearby starburst galaxy NGC253 with an XMM-Newton observation (Pietsch et al 2001). A Chandra ACIS image of the Antennae Galaxy (NGC4038/4039), a galaxy merger with a strong starburst, also shows many X-ray binaries (Fabbiano, Zezas & Murray 2001) which are responsible for the X-ray emission above 2 keV, and thus support the X-ray binary interpretation. The X-ray luminosity of the bright source in M82 in its high state (8.7 × 10^{40} erg s^{-1}) is comparable to the luminosity of the 2–10 keV tail in Arp220 (~1 × 10^{41} erg s^{-1}).

The lack of a strong Fe K line rules out the possibility of reflected emission from a hidden active nucleus. The upper limit of the 6.4 keV line (EW ≤ 600 eV) means that any reflection should be the order of half of or less than the observed X-ray emission around 6 keV, assuming standard cold reflection from optically thick cold matter with Solar abundance which would have a 6.4 keV line with EW ≃ 1 keV (e.g., George & Fabian 1991). The faint observed hard X-ray luminosity despite the large bolometric luminosity and suggested high star formation rate in this galaxy means that the inverse-Compton scattering, which has been proposed to account for the hard X-ray emission in starburst galaxies (e.g., Moran, Lehnert & Helfand 1999), may not be efficient. However, since this process depends on a number of parameters we do not know, it cannot be ruled out.

4.2 Weak soft X-ray emission

The relatively faint soft X-ray emission of Arp220 among powerful far-infrared galaxies, with some possible reasons, was discussed in Iwasawa (1999). Although whether (thermal) soft X-ray emission is a good measure of starburst intensity is not entirely clear, a reasonably good correlation between far-infrared and X-ray luminosities for star-forming galaxies has been reported (e.g., Griffiths & Padovani 1990). Here we make a further investigation using other 17 starburst galaxies for which soft X-ray data are available. Fig. 3 shows the \( L_{\text{SX}} - L_{\text{(FIR)}} \) relation for far-infrared luminous starburst galaxies (M82, NGC253, NGC1808, NGC2146, NGC2623, NGC3079, NGC3256, NGC3310, NGC3628, NGC3690, NGC4038/NGC4039, NGC4631, NGC4666, NGC4945, NGC6240, Mrk231, and Mrk273) and the correlation obtained for a sample of nearby Wolf-Rayet galaxies (Stevens & Strickland 1998). The soft X-ray (0.1–2 keV) lu-
Figure 4. The SED of Arp220 (crosses), NGC6240 (squares), and NGC4945 (triangles). The SED of NGC4945 has been scaled by multiplying by 80.4 for the 60–100\(\mu\)m luminosity to match Arp220; if NGC4945 were made to be as powerful as Arp220 at far-infrared wavelengths, the central source would have a similar luminosity to that in NGC6240. The soft X-ray decline of NGC4945 is due to large Galactic absorption (\(N_H \sim 1 \times 10^{21} \text{cm}^{-2}\)). Note that Arp220 is more luminous than NGC6240 in the far-infrared, but an order of magnitude less luminous in the soft X-ray band where starburst emission would appear.

Figure 3. Plot of the 0.1–2 keV luminosity (\(L_{\text{SX}}\)) against far-infrared luminosity (\(L_{\text{FIR}}\)) in powerful starburst galaxies (crosses) and Arp220 (filled square). The X-ray data obtained either from the ROSAT PSPC or BeppoSAX are collected from the literature. The far-infrared luminosities are calculated by the formula given in Dahlem et al (1998), based on the IRAS measurements at 60 and 100\(\mu\)m from the IRAS Faint Source Catalogue. The dotted line shows the correlation for the Wolf-Rayet galaxy sample of Stevens & Strickland (1998).

It is interesting to compare between the wide-band energy distributions of Arp220 and a similar far-infrared galaxy NGC6240, which is also a merger system with a comparable, but factor of 2 smaller, infrared luminosity (Fig. 4). The nuclei of both galaxies are classified as LINERs (e.g., Veilleux, Kim & Sanders 1998) and their optical, near-infrared to mid-infrared spectral features are dominated by starburst emission (Genzel et al 1998; Lutz, Veilleux & Genzel 1999; but also see Dudley 1999). The energy distributions of the two objects are rather similar from millimetre to optical bands, but differ significantly in the X-ray band (also in the radio band longward of several GHz, which could be due to free-free absorption). Firstly, the soft X-ray emission of Arp220 is about an order of magnitude below that of NGC6240, as demonstrated in Fig. 4. Secondly, in NGC6240, a heavily obscured active nucleus emerges in the hard X-ray band while the soft X-ray emission still originates from the starburst (Iwasawa & Comastri 1998; Vignati et al 1999). A recent Chandra HRC soft X-ray image of NGC6240 shows no point-like source but extended emission, suggesting thermal emission originating from the starburst to be a dominant.
soft X-ray source, although it could be a powerful photoionized nebula due to the hidden active nucleus, reminiscent of that in NGC1068 (Zezas et al 2001). Both galaxies show large-scale Hα/soft X-ray nebulae which are probably both produced by starburst-driven winds (“superwinds”, Heckman, Armus & Miley 1990; Heckman et al 1996). The luminosity of the Hα nebula of Arp220 is also an order of magnitude below that of NGC6240 (Heckman, Armus & Miley 1987). The near-infrared H$_2$ line luminosities of Arp220 and NGC6240 (e.g., Rieke et al 1985) also suggest that, if this line is shock-heated by the superwinds, the mechanical luminosity of the wind in Arp220 is a factor of $\sim 10$ smaller than in NGC6240. Therefore, in terms of the products of the superwinds, NGC6240 is much more powerful than Arp220, and yet possesses a powerful active nucleus hidden from direct view.

Besides the X-ray properties, following two points may highlights possible presence or absence of a massive central objects in the two galaxies. The stellar velocity dispersions inferred from the near-infrared CO band absorption features of NGC6240 ($\sigma \sim 360$ km s$^{-1}$) and Arp220 ($\sigma \sim 150$ km s$^{-1}$) are very different (Doyon et al 1994; Shier, Rieke & Rieke 1996). The dispersion velocity of NGC6240 is, in fact, unusually large compared with other infrared galaxies. This may indicate that NGC6240 has a massive object in the centre while Arp220 does not. The other is their radio morphology. NGC6240 shows two strong compact sources with diffuse emission (Colbert et al 1994) whilst many radio sources distributed over the galaxy, reminiscent of those in the nearby starburst galaxies M82 and NGC253, have been found in Arp220 (Smith et al 1998).

The nearby far-infrared galaxy NGC4945 is less powerful than Arp220 and NGC6240 but has similar characteristics and is a prototype of active nuclei with absorption column density exceeding $10^{24}$ cm$^{-2}$. Interestingly, the hard X-ray ($\sim 20$–150 keV) and radio emission of NGC4945 would compare with that of NGC6240, when the SED of NGC4945 is scaled for the 60–100$\mu$m luminosity to match Arp220 (Fig. 4).

Among possible explanations for the small soft X-ray luminosity in Arp220 are 1) an obscuration in the X-ray nebula; 2) a dense environment for the star forming region; 3) the age of the starburst; 4) metallicity effects; and 5) a weak starburst. These possibilities are discussed below.

Observed soft X-ray emission is subject to photoelectric absorption and could easily be suppressed by an order of magnitude. Although the soft X-ray emission in Arp220 is extended over a 20 kpc scale (Heckman, Armus & Miley 1987), if it is emitted from a number of small, dusty clumps (see Strickland et al 2000 for the case of NGC253), suppression of thermal X-ray emission is possible through absorption within the individual clumps. A study of NaD absorption features in starburst galaxies by Heckman et al (2000) suggests that the column density is a few times of $10^{27}$ cm$^{-2}$. However, the absorption feature due to the interstellar medium is shallower in Arp220 than in NGC6240. Therefore, as far as the comparison between the two galaxies is concerned, there is no reason why the Hα/X-ray nebula of Arp220 should be more obscured than NGC6240. Since the extended HI gas around Arp220 avoids the superwind region (Hibbard, Vacca & Yun 2000), absorption by this HI gas is also unlikely. Properties of the obscured starburst region itself are constrained by ionizing photon arguments (Shioya, Trentham & Taniguchi 2001) and the millimetre emission measurement (Scoville, Yun & Bryant 1997). We note that the 5–10 keV X-ray emission is least absorbed and so should be a good direct probe of starburst activity.

To yield the faint superwind features, the mechanical luminosity emerged outside the starburst region for heating the ISM should be small (since the superwind-heated soft X-ray luminosity is almost proportional to the mechanical luminosity, see Heckman et al 1996). Perhaps an unusually dense environment in the starburst region in Arp220 suppresses the conversion from the mechanical energy of supernovae and stellar winds to that driving the superwind, due to less effective thermalization than in other superwind galaxies. The energy lost here goes to UV radiation via fast cooling of the dense medium, which, in turn, heats surrounding dust and increases the infrared emission. This could make a fainter superwind-heated X-ray nebula and more luminous infrared dust radiation, i.e., a larger $L_{\text{IR}}/L_{\text{SX}}$, than in a lower density medium for which the initial thermalization is efficient. The condition for this to occur (cooling time becomes shorter than expansion timescale) would be the density of the interstellar medium being larger than $\sim 10^6$ cm$^{-3}$ (e.g., Fabian & Terlevich 1996), which is, however, much larger than $2 \times 10^5$ cm$^{-3}$ estimated for the nuclear molecular disk (Scoville et al 1997).

X-ray production by a starburst somewhat delays through thermalization of the core injection region and formation of X-ray binaries. The evolution of X-ray emission due to starburst-driven winds is computed by Strickland & Stevens (2000) and X-ray properties as a function of merger evolution are discussed in Read & Ponman (1998). It is possible that about one order of magnitude variation in X-ray luminosity occurs after a burst of star formation. However, since the far-infrared luminosity reflects on-going star formation, finding a match between large $L_{\text{IR}}$ and a small $L_{\text{SX}}$ as seen in Arp220 appears to be difficult. A study of molecular gas dynamics suggests that the galaxy merger in NGC6240 is in an earlier stage than in Arp220 and an even more intensive star formation is still to come in NGC6240 as the merger advances (Tacconi et al 1999). This predicts an increase in the far-infrared luminosity of NGC6240 to rival Arp220 but does not seem to help the soft X-ray emission in NGC6240, which is already one order of magnitude more luminous than Arp220, to decline to match that of Arp220, unless there is an unknown mechanism to suppress the soft X-ray production during the peak of star formation.

Metallicity affects the emissivity of the hot gas (e.g., Strickland & Stevens 2000). However, the evident Fe-L emission in the soft X-ray spectrum rules out an anomalously low metallicity in the X-ray nebula. The massive X-ray binary population appears to depend in part on the metallicity of a galaxy (Clarke et al 1978). This could be due to effects on the initial mass function, binary evolution or on stellar wind rates. Unusually high metallicity is needed to suppress the formation of X-ray binaries.

The last possibility of a weak starburst leaves an accretion-powered massive black hole to play a significant role in the energetics in Arp220. Despite the lack of AGN features in any waveband, this is still viable, although it is hard to prove. A central source must be thoroughly buried in heavy obscuration. Since the central part of Arp220 is
extremely rich in molecular gas (Sanders, Scoville & Soifer 1991; Solomon, Radford & Downes 1992), there is no shortage in supply for such obscuring material. Here it is interesting to note that the dense molecular gas in Arp220 is in the shape of a thin disk with a radius $\sim 200$ pc containing the two nuclei (Scoville, Yun & Bryant 1997), while in NGC6240, the highest molecular concentration occurs between the two nuclei (Tacconi et al 1999), which may cause a difference in their nuclear obscuration. The optical depth of the dust shrouds must be large so that the temperature of the dust reradiation we are seeing is cool as observed, and the covering factor must also be almost unity in order not to expose a hot dust region. Under this condition, the PAH emission, which is observed strongly (Strum et al 1996; Genzel et al 1998), should not be destroyed by X-ray irradiation (Voit 1992) and the photon-excess problem due to AGN discussed by Shioya et al (2001) would become irrelevant. A large covering factor of the obscuration is also required to explain the lack of reflected X-ray light, i.e., there should be little light escaping from the nuclear obscuration to be scattered into our line of sight. One of the few recognizable spectral features expected other than black body emission is a deep silicate absorption feature at 10$\mu$m, which is indeed observed and a scaled-up protostar model can explain the mid-infrared spectrum of Arp220 (Dudley & Wynn-Williams 1997).

Since we detected neither absorbed hard X-ray emission nor reflection from such an active nucleus, the only viable solution is to have a Compton-thick source without significant reflected light. In the next subsection, we use the PDS upper limit to constrain the properties of such an X-ray nucleus, if present.

4.3 Hard X-ray constraint on a hidden active nucleus

The hard X-ray flux limit implied from the PDS data depends on assumed spectral models. In the interest of an absorbed power-law component, we first estimate the lowest possible $N_H$ value. Suppose the PDS upper limit was real and no emission from such an absorbed source is detected with the MECS (see the previous subsection), then a lower bound of absorption column density could be estimated by combining with the MECS data at the high energy end (say 7–10 keV data). When a photon index of $\Gamma = 2$ is assumed for the absorbed power-law, the lower limit of $N_H$ is $2 \times 10^{24}$ cm$^{-2}$, where the effect of Compton scattering in a spherical obscuration is taken into account (Math et al 1999). The 13–50 keV flux for the PDS upper limit is then $3.5 \times 10^{-12}$ erg cm$^{-2}$ s$^{-1}$ (or $2.1 \times 10^{12}$ erg s$^{-1}$ in luminosity).

We then estimate the absorption-corrected 2–10 keV luminosity of the power-law source with various absorption column densities larger than the lower limit value obtained above. Spherical obscuration is assumed for all cases. The 2–10 keV luminosity is then converted to bolometric luminosity, assuming a typical energy distribution of Seyfert galaxies and QSOs (e.g., Elvis et al 1994). A reasonable range of the $L_{2-10\text{keV}}/L_{\text{bol}}$ ratio is 3 to 10 per cent. Provided all the absorbed radiation from an obscured source is reradiated in the infrared band, the upper limit the AGN fraction powering the infrared luminosity of Arp220 can be plotted as a function of absorption column density (Fig. 5). This plot shows that the column density must exceed $10^{25}$ cm$^{-2}$ for a spherically-obscured active nucleus to be the major power source in Arp220. In this case, the column density is so high that Compton down-scattering suppresses the transmitted light to an undetectable level. As mentioned in the Introduction, even if cold reflection is present, the limit obtained from the MECS data predicts its flux level well below the PDS detection limit.

If the hard X-ray source in NGC1068 ($\sim 0.2$ ct s$^{-1}$ detected by the BeppoSAX PDS, Math et al 1997), a Compton-thick AGN with no transmitted hard X-ray component at the distance of 14 Mpc, is scaled by the $L_{\text{ir}}$ and located at the distance of Arp220, then the expected PDS count rate is $\sim 0.05$ ct s$^{-1}$, which is consistent with no significant detection in the PDS data.

5 SUMMARY

Neither a strong Fe K line nor hard X-ray excess emission is detected from Arp220 with BeppoSAX. Although the lack of AGN signatures points to a starburst being a major energy source of the luminous infrared emission, the weakness of the soft X-ray emission, which should also be powered by the starburst, remains puzzling. In the context of starburst outflow, Arp220 does not appear to be as powerful as expected from the large infrared luminosity. An alternative is that much of the bolometric luminosity is powered by an active nucleus entirely obscured by thick absorbing matter, which must exceed $10^{25}$ cm$^{-2}$.

ACKNOWLEDGEMENTS

We thank Dave Sanders, Joss Bland-Hawthorn, Neil Trentham and Yoshiaki Taniguchi for useful discussion. This research has made use of the NASA/IPAC Extragalactic Database (NED) which is operated by the Jet Propulsion Laboratory of the California Institute of Technology, under contract with the National Aeronautics and Space Administration.
Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration. PPARC (KI) and Royal Society (ACF) are thanked for support.

REFERENCES

Awaki H., Ueno S., Koyama K., Tsuru T., Iwasawa K., 1996, PASJ, 48, 409
Boella G., Butler R.C., Perola G.C., Piro L., Scarsi L., Bleeker J.A.M., 1997, A&AS, 122, 299
Clarke G., Doyon R., Ells M., Wright G.S., Joseph R.D., Nadeau D., James P.A., 1994, ApJ, 437, L23
Dahlem M., Weaver K.A., 1998, ApJS, 118, 401
Dahlem M., Parmar A., Oosterbroek T., Orr A., Weaver K.A., Heckman T.M., 2000, ApJ, 538, 555
Della Ceca R., Griffiths R.E., Heckman T.M., Lehner M.D., Weaver K.A., 1997, ApJ, 514, L21
Deller C.C., Bland-Hawthorn J., Chiang J., McNaron-Brown K., 1997, ApJ, 484, L121
Dickey J.M., Lockman F.J., 1990, ARAA, 28, 215
Doyon R., Eills M., Wright G.S., Joseph R.D., Nadeau D., James P.A., 1994, ApJ, 437, L23
Dudley C.C., Wyn-Williams C.G., 1997, ApJ, 488, 720
Dudley C.C., 1999, MNRAS, 307, 553
Elvis M., et al, 1994, ApJS, 95, 1
Fabian A.G., Zezas A., Murray S.S., 2001, ApJ, in press (astro-ph/0102256)
Fabian A.C., Terlevich R., 1996, MNRAS, 280, L5
Genzel R., et al, 1998, ApJ, 498, 579
Guainazzi M., Matteuzzi A., 1997, SDC-TR-011
Guainazzi M., Matt G., Brandt W.N., Antonelli L.A., Barr P., Bassani L., 2000, A&A, 356, 463
George I.M., Fabian A.C., 1991, MNRAS, 249, 352
Heckman T.M., Armus L., Miley G.K., 1987, AJ, 93, 276
Heckman T.M., Armus L., Miley G.K., 1990, ApJS, 74, 833
Heckman T.M., Dahlem M., Eales S.A., Fabbiano G., Weaver K.A., 1996, ApJ, 457, 616
Heckman T.M., Armus L., Weaver K.A., Wang J., 1999, ApJ, 517, 130
Heckman T.M., Lehner M.D., Strickland D.K., Armus L., 2000, ApJS, 129, 493
Hibbard J.E., Vacca W.D., Yun M.S., 2000, AJ, 119, 1130
Iwasawa K. Koyama K., Awaki H., Kunieda H., Makishima K., Tsuru T. Ohashi T. Nakai N., 1993, ApJ, 409, 155
Iwasawa K., Comastri A., 1998, MNRAS, 297, 1219
Iwasawa K., 1999, MNRAS, 302, 96
Lutz D., Veilleux S., Genzel R., 1999, ApJ, 517, L13
Malolino M., Marconi A., Salvidi M., Risaliti G., Severgnini P., Oliva E., La Franca F., Vanzl L., 2001, A&A, 365, 28
Matsumoto H., Tsuru T.G., 1999, PASJ, 51, 321
Matsumoto H., et al, 2001, ApJ, 547, L25
Matt G., et al, 1997, A&A, 325, L13
Matt G., Pompilio F., La Franca F., 1999, New Astronomy, 4, 191
Matt G., 2000, A&A, 355, L31
Moran E.C., Lehnaert M.D., Helfand D.J., 1999, ApJ, 526, 649
Ohyama Y., Taniguchi Y., Hibbard J.E., Vacca W.D., 1999, AJ, 117, 2617
Pier E., Krolik J.H., 1992, ApJ, 401, 99
Pietsch W. et al, 2001, A&A, 365, L174
Ptak A., Griffiths R., 1999, ApJ, 517, L85
Read A.M., Ponman T.J., 1998, MNRAS, 297, 143
Rieke G., 1988, ApJ, 331, L5
Sanders D.B., Mirabel I.F., 1996, ARAA, 34, 749
Sanders D.B., Scoville N.Z., Soifer B.T., 1991, 370, 158
Sansom A., Dotani T., Okada K., Yamashita A., Fabbiano G., 1996, MNRAS, 281, 48
Scoville N.Z., Yun M.S., Bryant P.M., 1997, ApJ, 484, 702
Soifer B.T., Sanders D.B., Madore B.F., Neugebauer G., Danielson G.E., Elias J.H., Lonsdale C.J., Rice W.L., 1987, ApJ, 320, 238
Solomon P.M., Downes D., Radford S.J.E., 1992, ApJ, 387, L55
Smith H.E., Lonsdale C.J., Lonsdale C.J., Diamond P.J., 1998, ApJ, L17
Stevens I.R., Strickland D.K., 1998, MNRAS, 294, 523
Shier L.M., Rieke M.J., Rieke G.H., 1996, ApJ, 470, 222
Shioya Y., Trentham N., Taniguchi Y., 2001, ApJ, 548, L29
Strickland D.K. Stevens I.R., 2000, MNRAS, 314, 511
Strickland D.K., Heckman T.M., Weaver K.A., Dahlem M., 2000, AJ, 120, 2965
Sturm E., et al, 1996, A&A, 315, L133
Tacconi L.J., Genzel R., Tezca M., Gallimore J.F., Downes D., Scoville N.Z., 1999, ApJ, 524, 732
Turner T.J., George I.M., Nandra K., Mushotzky R.F., 1997, ApJS, 113, 23
Veilleux S., Kim D.-C., Sanders D.B., 1998, ApJ, 522, 113
Vignati P., et al, 1999, A&A, 349, L57
Voll G.M., 1992, MNRAS, 258, 841
Zezas A.L., Georgantopoulos I., Ward M.J., 1998, MNRAS, 301, 915
Zezas A., Ward M.J., Lira P., Fraser G., Ueno S., 2001, in proc of X-ray Astronomy 2000, PASP Conference Series, eds R. Giacconi, L. Stella and S. Serio