The *BeppoSAX* spectrum of the composite galaxy Mrk 609

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Accepted 2002 April 26. Received 2002 April 26; in original form 2001 November 16

ABSTRACT

We present *BeppoSAX* observations of the starburst/Seyfert composite galaxy Mrk 609. This enigmatic object has an optical spectrum dominated by the features of starburst galaxies, yet its X-ray luminosity \((6.3 \times 10^{42} \text{ erg s}^{-1})\) is typical of an active galactic nucleus (AGN). The X-ray spectrum of Mrk 609 can be parametrized by a single-power-law model with a photon index \(\Gamma \sim 1.6 \pm 0.1\) and no evidence for significant absorption above the Galactic value. Long-term variability in both the 0.1–2 and 2–10 keV energy bands is detected, again suggesting that the X-ray emission is dominated by an AGN. The observed broad Hα component is a factor of 40 below that predicted by the X-ray flux, implying a deficit of ionizing ultraviolet photons.

Key words: galaxies: active – galaxies: individual: Mrk 609 – galaxies: starburst – X-rays: galaxies.

1 INTRODUCTION

Moran, Halpern & Helfand (1996), after careful spectroscopy of a sample based on the cross-correlation of the *IRAS* Point Source Catalog (PSC) and *ROSAT* All-Sky Survey, reported the discovery of an ‘anomalous’ class of objects. The optical spectra of these sources are dominated by the features of starburst galaxies, based on the emission-line diagnostic diagrams (Veilleux & Osterbrock 1987), yet their X-ray luminosities are typical of Seyfert 2 galaxies. Close examination of their optical spectra reveals some weak Seyfert-like features: [OIII] significantly broader than all other narrow lines in the spectrum and in some cases a weak broad Hα component. The authors designated these objects ‘starburst/Seyfert composite’ galaxies and presented them as a new class of X-ray-luminous source. Similar ‘composite’ objects have also been noticed by Véron, Gonçalves & Véron-Cetty (1997). Indeed, they presented observations of 15 objects with transition spectra, i.e. showing the simultaneous presence of a strong star-forming component and an active nucleus, and they showed that the objects fall either on the starburst region or on the borderlines between the different classes. Hereafter, we will refer to these objects as composite galaxies, and we will distinguish them from the Seyfert 2/starburst galaxies that show emission from both components at all wavelengths.

The composite galaxies bear close resemblance to the narrow-line X-ray galaxies (NLXGs) detected in large numbers in deep *ROSAT* surveys (e.g. Boyle et al. 1995; Griffiths et al. 1996). These NLXGs again have spectra that are composites of those of Seyfert and starburst galaxies (Boyle et al. 1995) with luminosities \(L_{2–10\text{keV}} \sim 10^{42–43} \text{ erg s}^{-1}\). Unfortunately the faint fluxes of these NLXGs do not allow their detailed study at either optical or X-ray wavelengths. Although it is unclear whether these nearby ‘composites’ are the same class of objects as those found in *ROSAT* deep field NLXGs, their high luminosities need to be explained. It is unclear how their intense X-ray emission can be reconciled with weak or absent Seyfert characteristics.

1.1 Composite galaxies in X-rays

Only a few composite galaxies have been studied so far in X-rays. Specifically, *IRAS* 00317 + 684 (Georgantopoulos 2000) has been observed with *ASCA* and is the most luminous object \((L_x \approx 10^{43} \text{ erg s}^{-1}\) in the 0.1–2 keV band) in the Moran et al. (1996) sample. The spectrum is represented by a power law with \(\Gamma \sim 1.76\) and there is no evidence for absorption above the Galactic value. Strong variability in the 1–2 keV band (by a factor of 3) is detected between the *ROSAT* and *ASCA* observations. These characteristics indicate an active galactic nucleus (AGN) origin for the X-ray emission. However, no iron line is detected, and the 90 per cent upper limit on the equivalent width is 0.9 keV. The ratio \(f_{\text{HX}}/f_{\text{0.684}}\sim 2.5\) rules out the Compton-thick interpretation for *IRAS* 00317 + 2142. However, the precise nature of this object and the relative contributions of the starburst and AGN components cannot be determined.

A further composite object studied in X-rays with *ROSAT* and *ASCA* is AX J1749 + 684 (Iwasawa et al. 1997). AX J1749 + 684 was serendipitously detected with the *ASCA* Gas Imaging Spectrometer (GIS). Its X-ray spectrum is flat \((\Gamma = 1.23_{-0.21}^{+0.22})\). The flatness is attributed by the authors to absorption mainly because of (i) the large Balmer decrement in the narrow-line region, \(H_\alpha/H_\beta = 7.32\), and (ii) the lack of significant X-ray detection at \(<0.4\) keV. On the other hand, the optical counterpart of AX J1749 + 684 is detected in...
the Kiso Schmidt Survey of ultraviolet-excess galaxies. Iwasawa et al. (1997) claimed that the ultraviolet emission is due to large-scale starburst activity; in this case, however, strong far-infrared emission should be expected, which is inconsistent with the non-detection of this source by IRAS. They concluded that the X-ray spectrum of AX J1749 + 684 is well fitted by an obscured (NH = 2.1^{+5.2}_{−2.1} × 10^{21} cm^{-2}) Seyfert nucleus embedded within a star-forming galaxy.

Recently, Levenson et al. (2001) examined NGC 6221 as a further example of a composite galaxy. They proposed that the X-ray spectrum of this object is characterized by a Seyfert 1-like spectrum. They detected an iron line and continuum variability on short- and long-term time-scales. The source has a column density of NH = 10^{22} cm^{-2}. Levenson et al. proposed that the central region is obscured by a surrounding starburst. Thus the optical spectrum has the characteristics of the starburst component alone.

1.2 Mrk 609

Mrk 609 is at a redshift of 0.034. The optical position of the object is 03:25:25.3, +1.96:08:39 (J2000) and the Galactic absorption is NH = 4.41 × 10^{20} cm^{-2}. The Hβ profile is ~110 km s^{-1} wide, while the [O III] lines are ~4 times wider. In addition, the broad blueshifted wings seen on the [O III] lines are completely missing in Hβ (Heckman et al. 1981). The ultraviolet spectrum shows a strong contribution from hot stars (Rudy, Cohen & Ake 1988), indicating the presence of an intense starburst component in Mrk 609.

The broad Hα/Hβ value is 7.8 (Osterbrock 1981). In a later observation, Rudy et al. (1988) obtained a value for the broad Hα/Hβ = 5. The discrepancy was attributed to continuum variability. The high broad Hα/Hβ value was attributed by Osterbrock (1981) to reddening of the broad-line region. However, the broad Lyα/Hβ value is 16, which is large for Seyfert 1 galaxies, ruling out obscuration [see Rudy et al. (1988) for a detailed discussion].

2 OBSERVATIONS AND DATA REDUCTION

Mrk 609 was observed by BeppoSAX three times. The first observation was carried out on 2000 January 20 for ~18 ks [Low Energy Concentrator Spectrometer (LECS) exposure 7.13 ks], the second one on 2000 February 14 for ~2.5 ks (LECS exposure 1.4 ks) and the third one on 2000 March 4 for ~28 ks (LECS exposure 6668 ks). It should be noted here that the exposure time for the LECS is lower than that for the Medium Energy Concentrator Spectrometer (MECS) because it is limited by stronger operational constraints to avoid ultraviolet light contamination, thus it is operated during Earth dark time only. Spectra and light curves of Mrk 609 have been extracted from circular regions centred on the source. We used a circular extraction cell of 4 and 6 arcmin in radius for MECS and LECS data respectively. The background spectra were extracted from blank deep-field exposures, using the same region of the detector in each case.

In order to check whether there is any flux or spectral variability in the soft band, an unpublished ROSAT Position Sensitive Proportional Counter (PSPC) observation of Mrk 609 was analysed. Mrk 609 was observed by ROSAT on 1997 January 29 for 5801 s. A source spectrum was extracted from a circular region of ~1.5-arcmin radius around the centroid of the source, while the background spectrum was extracted from an annulus of internal and external radii 3 and 9 arcmin respectively.

3 VARIABILITY

In order to investigate the nature of the X-ray source, we constructed the long-term light curves of Mrk 609. Then the variability was tested by means of a χ^2 test against the hypothesis that the flux was constant. The χ^2 values are quoted in Table 1 for four light curves: LECS 0.1–2 keV, MECS 2–10 keV, MECS 2–5 keV and MECS 5–10 keV. The MECS data were split into three different bands in order to check whether there are different components contributing to the variability of the source. Fig. 1 shows the light curves in the four energy bands. The points are in chronological order, and the errors are based on counting statistics only.

It is evident that Mrk 609 is variable at both soft and hard energies. In the LECS the flux is decreasing and the difference in flux between the first and third observations is about a factor of 2. Significant variability at the ~99.9 per cent confidence level is detected in the 2–10 and 2–5 keV energy bands, whereas the variability in the 5–10 keV band is significant only at the 57 per cent confidence level. In the three hard bands the variability follows the same trend: the first and third observations have comparable fluxes, whereas during the second observation the flux drops by up to a factor of 3. This suggests that the whole of the hard X-ray emission is produced by the same mechanism and in the same region. However, the variability in the soft band follows a different trend from the hard band, suggesting that emission in the two bands is produced by different mechanisms and in different regions.

We also checked for short-time-scale variability. Mrk 609 does not show evidence for short-time-scale variability at a significant level. This is probably due to the low statistics.

4 SPECTRAL ANALYSIS

The spectral fitting was performed in the 0.12–10 keV band. The appropriate redistributions matrix file and the ancillary response file for the observation date were obtained from the BeppoSAX Science Data Centre archive. A summary of the spectral fitting results is given in Table 2. In the following analysis all three BeppoSAX observations are fitted together.

Throughout this paper values of H0 = 75 km s^{-1} Mpc^{-1} and q0 = 0.5 are assumed.

4.1 The AGN models

We first fitted the data with a single-power-law model (PL). We obtained an acceptable fit (χ^2 = 98.89 for 82 d.o.f.) with Γ = 1.57^{+0.10}_{−0.10} and N_H ≤ 1.32 × 10^{21} cm^{-2}. This model, together with the data points and the data-to-model ratio, is plotted in Fig. 2. The observed flux in the 2–10 keV band for this model is 2.86 × 10^{-12} erg s^{-1} cm^{-2}, which corresponds to a luminosity of 6.3 × 10^{37} erg s^{-1} in the same band. If the slope of the PL model is fixed at a value of 1.9, the nominal value for Seyfert 1 galaxies (Nandra & Pounds 1994), the model yields an unacceptable fit (χ^2 = 119.26 for 83 d.o.f.) with N_H = 2.03^{+1.5}_{−1.8} × 10^{21} cm^{-2}.

Although Seyfert galaxies show strong narrow iron Kα emission lines, no such line is detected in Mrk 609. However, an upper limit of ~283 eV is obtained, consistent with values seen in Seyfert galaxies.
In the context of the unified models, we expect to see some fraction of the primary emission through the torus, with a component superimposed upon this that represents a fraction of emission scattered back into our line of sight by material lying above the torus. This model is represented by two power laws with the same photon index but different normalizations and absorptions – the scattering model. When this model is applied to the data, the normalizations of the two power laws are comparable, whereas no excess absorption above the Galactic value is required and thus this model effectively is the same as the single PL model. Therefore it is evident that the scattering model does not provide a good representation of the data.

Finally, an ionized warm absorber model in addition to the Galactic column density was fitted to the data (PL + warm). The temperature of the absorber is fixed at $T = 10^5$ K (Brandt et al. 1997). The model provides an acceptable fit ($\chi^2 = 98.84$ for 81 d.o.f.) but does not represent a statistically significant improvement to the single-PL model. The best-fitting parameters are $\Gamma = 1.60^{+0.16}_{-0.12}$ and a warm column density $N_{\text{Hw}} = 6.73^{+2.47}_{-1.87} \times 10^{21}$ cm$^{-2}$, while the ionization parameter is practically unconstrained, possibly because of the poor statistics of the data.

4.2 The composite model

Given the composite classification of this object, it is natural to investigate a model in which X-ray emission originates from both a starburst and an AGN. A power law plus a Raymond–Smith model (PL+RS) with the temperature fixed at 0.8 keV is adopted. The
Table 2. The spectral fit results for the BeppoSAX data.

| Model       | $\Gamma$    | $N_H^a$ | $N_H^b$ | $\xi$ | $kT_{\text{RS}}$ | $\chi^2$ (d.o.f.) |
|-------------|--------------|---------|---------|-------|------------------|-------------------|
| Single PL   | $1.57^{+0.10}_{-0.10}$ | $\leq 1.32$ | $-3.51^{+0.73}_{-1.32}$ | $-2.39$ | $-2.13$ | $98.89$ (82) |
| PL + warm   | $1.60^{+0.16}_{-0.12}$ | $g$ | $\leq 369.11$ | $\geq 0$ | $-1.9f$ | $97.90$ (81) |
| PL + RS     | $1.57^{+0.09}_{-0.11}$ | $g$ | $-3.51^{+0.73}_{-1.32}$ | $-2.39$ | $-2.13$ | $99.00$ (81) |
| RS          | $-3.51^{+0.73}_{-1.32}$ | $g$ | $-3.51^{+0.73}_{-1.32}$ | $-2.39$ | $-2.13$ | $108.94$ (83) |
| 2RS         | $-3.51^{+0.73}_{-1.32}$ | $g$ | $-3.51^{+0.73}_{-1.32}$ | $-2.39$ | $-2.13$ | $105.57$ (80) |

Note: $g$ indicates that $N_H$ is set to the Galactic value.

$^a$Column density is in units of $10^{21} \text{ cm}^{-2}$.

$^b$Column density in the warm medium is in units of $10^{21} \text{ cm}^{-2}$.

Figure 2. The BeppoSAX time-averaged spectrum, when the single-PL model is applied to the data. The filled squares represent the LECS data points and the stars the MECS data points. The top panel shows the data with the model and the bottom panel shows the data/model ratio.

power-law component is allowed to have additional absorption over and above that of the thermal component. This model yields an acceptable fit ($\chi^2 = 99.81$ for 81 d.o.f.) with $\Gamma = 1.57^{+0.09}_{-0.11}$ whereas no excess absorption above the Galactic value is required. When the temperature of the thermal component is a free parameter, we find $kT > 18 \text{ keV}$ and $\Gamma = 2.81^{+2.59}_{-0.96}$ ($\chi^2 = 95.00$ for 80 d.o.f.). However, the temperature of the thermal component is far too high for a starburst, and thus this model cannot provide a physical description of the data.

4.3 The pure starburst model

For completeness we have also investigated pure starburst models. First a single RS model was fitted to the data. An acceptable fit was obtained ($\chi^2 = 108.94$ for 83 d.o.f.) with $kT_1 = 18.92^{+10.05}_{-6.02}$ keV. No starbursts with such a high temperature have been found as yet.

Then a two-RS model representing thermal emission from a pure starburst galaxy following Zezas et al. (1998) was utilized. The soft emission is parametrized by a thermal component with $kT_1 \leq 1 \text{ keV}$ and the emission in the hard band by $kT_2 = 21.8^{+14.33}_{-7.69}$ keV, again too high for a starburst. Therefore it is obvious that this model cannot provide a physical description of the data.

From the above it is evident that the pure starburst model is ruled out, whereas the composite model does not provide a physically acceptable model.

5 SPECTRAL VARIABILITY

Mrk 609 was observed three times with BeppoSAX, allowing us to examine whether there is spectral variability. In particular it is interesting to see whether the drop in the flux during the second observation is related to a change in the spectrum of Mrk 609, and examine whether the X-ray behaviour is similar to that of black hole candidates (BHCs) in our Galaxy during their high and low states.

For this analysis only the single power law is applied to the MECS data. In addition, any spectral variability at soft energies can be examined by comparing the ROSAT PSPC and LECS data. For that reason
we analysed an unpublished observation of Mrk 609 with ROSAT, as explained in Section 2.

5.1 Observation 1

The PL model yields a fit ($\chi^2 = 55.75$ for 38 d.o.f.) with $\Gamma = 1.63^{+0.16}_{-0.10}$ and Galactic absorption. The observed flux in the 2–10 keV band for this model is $2.85 \times 10^{-12}$ erg s$^{-1}$ cm$^{-2}$, which corresponds to a luminosity of $6.32 \times 10^{42}$ erg s$^{-1}$ in the same band. We do not detect an iron line at 6.4 keV but we obtain an upper limit of 540 eV.

5.2 Observation 2

During the second observation Mrk 609 was observed for $\sim$2.5 ks only, and no reliable spectrum could be extracted. However, clues for the spectral shape of the spectrum of Mrk 609 during this short observation come from the hardness ratio (HR) of the source. Here HR is defined as $h - s/h + s$, where $h$ and $s$ are the total number of counts, in the 2–10 and 1–2 keV bands respectively. Only MECS data were used since Mrk 609 is not detected in the LECS. The HR is 0.31 $\pm$ 0.18, which corresponds to a power law of $\Gamma = 1.2 \pm 0.70$ assuming Galactic absorption. Unfortunately, the uncertainty in the value of $\Gamma$ is too high for any firm conclusion about spectral changes to be derived.

5.3 Observation 3

The PL model yields a $\Gamma = 1.64^{+0.14}_{-0.12}$ and Galactic absorption ($\chi^2 = 61.16$ for 48 d.o.f.). The observed flux in the 2–10 keV band for this model is $2.72 \times 10^{-12}$ erg s$^{-1}$ cm$^{-2}$, which corresponds to a luminosity of $6.02 \times 10^{42}$ erg s$^{-1}$ in the same band. In the energy range 6–7 keV there is some evidence for residuals. So a Gaussian line was added to the model. The best-fitting energy for the line is 6.73$^{+0.22}_{-0.24}$ keV, clearly inconsistent with the line originating from cold iron. The model is acceptable ($\chi^2 = 56.31$ for 46 d.o.f.) with $\Gamma = 1.70^{+0.19}_{-0.12}$ and an equivalent width for the iron line of $394^{+291}_{-286}$ eV.

5.4 LECS/PSPC spectra comparison

The ROSAT spectrum is well represented by a single power law with $\Gamma = 2.02^{+0.24}_{-0.23}$, steeper than the BeppoSAX spectrum ($\Gamma \sim 1.6$). However, owing to the poor statistics of the LECS data compared with the MECS data, the spectral slope of the former is probably driven by the latter and thus the discrepancy might not be real. Therefore, in order to check whether the PSPC and LECS slopes are inconsistent, we fit the LECS data alone with a single PL model in the 0.12–2.0 keV energy range. The best-fitting parameters are $\Gamma = 1.97^{+0.51}_{-0.54}$ and Galactic absorption ($\chi^2 = 3.22$ for six d.o.f.). Owing to error uncertainties the slope is consistent with both the PSPC and MECS slopes, and thus any variability between the ROSAT and BeppoSAX observations as well as any spectral upturn within the BeppoSAX observations cannot be examined.

6 DISCUSSION

Mrk 609 displays an X-ray continuum, which is somewhat at odds with its optically composite nature. A simple power law is a good description of the data over the whole 0.1–10 keV energy range, with a rather flat index ($\Gamma = 1.57^{+0.10}_{-0.10}$). Still, this value is not inconsistent with those encountered in Seyfert 1 spectra (Nandra & Pounds 1994). Moreover, no iron emission line is detected when all three observations are fitted together and the upper limit of the equivalent width of the line is $\sim$283 eV. For the third observation, where the data-to-model ratio shows line-like residuals in the 6–7 keV band, the inclusion of the iron line improves the fit significantly. The best-fitting line is 6.72$^{+0.22}_{-0.24}$ keV with an equivalent width of $394^{+291}_{-286}$ eV. Nevertheless, the detection of significant X-ray variability confirms that a supermassive black hole resides in Mrk 609 and powers the X-ray emission, and rules out a significant contribution from a starburst component to the X-ray emission.

The data do not allow us to constrain the X-ray column density and we obtain a 90 per cent upper limit of $1.3 \times 10^{22}$ cm$^{-2}$. However, optical and ultraviolet observations are in favour of low obscuration towards the central engine. Indeed, Rudy et al. (1988) find a high Ly$\alpha$/H$\alpha$ ratio, implying that the optical reddening is negligible.

Recently, Levenson et al. (2001) proposed an ‘obscuring starburst model’ to explain the multiwavelength properties of the composite galaxy NGC 6221. According to their model NGC 6221 is a Seyfert 1 galaxy which is surrounded by a starburst component. The starburst accounts for the X-ray obscuration ($N_H \sim 10^{22}$ cm$^{-2}$) and its characteristics dominate the optical spectrum. Although in principle this model can explain qualitatively the optical appearance of the composite galaxies, it does not seem to fit the X-ray observations of Mrk 609. Our object does not show concrete evidence for significant X-ray absorption. In addition, the soft X-ray variability and the high luminosity at low energies ($L_{0.5–2keV} \sim 2 \times 10^{42}$ erg s$^{-1}$) probably rule out a dusty obscuring circumnuclear starburst. We note here that the spectral X-ray properties of Mrk 609 are similar to those of the composite IRAS 00317–2142 (Georgantopoulos 2000). Again this galaxy has a low column density, consistent with the Galactic value, and thus the obscuring starburst model cannot explain the properties of IRAS 00317–2142.

Although the single-PL model yields a good representation of the Mrk 609 spectrum, the X-ray long-term variability indicates that the spectrum of Mrk 609 consists of more than one component. An AGN covered by a warm absorbing screen could provide an explanation for the observed long-term variability. In this case, changes in the X-ray continuum flux will be followed by changes in the ionization state of the warm absorber, resulting in changes in the emission in the soft band. However, the quality of the data does not allow an examination of the viability of the model for Mrk 609.

Given the composite nature of Mrk 609, it is natural to investigate whether emission from starburst regions contributes to the X-ray wavelengths. In principle, in a composite starburst–AGN model, the power-law component is heavily absorbed, and thus the starforming component, which is located outside the obscuring screen, dominates the soft emission. However, when this model is applied to the Mrk 609 data, no excess absorption above the Galactic value is required by the data for the power-law component. In addition, the poor quality of the data at energies below $\sim$2 keV does not allow us to constrain the temperature of the thermal emission and make an unambiguous estimate of the starburst contribution to the X-ray emission. The strength of the star-forming component can be indirectly estimated from the observed infrared flux. The expected X-ray contribution from stars was calculated using the empirical relationship between infrared and X-ray luminosity [equation (2) of David, Jones & Forman 1992] found in a sample of IRAS galaxies. However, note that some of the infrared flux could arise from nuclear reprocessed emission from the obscuring medium. Thus any starburst contribution to the X-ray flux derived using the above relation may be overestimated and the derived flux should only be treated as an upper limit. First we calculated the infrared luminosities using the IRAS fluxes at 60 and 100 $\mu$m and equation (1) from David et al.
explained. Using a steep X-ray spectrum and no significant X-ray absorption. If the narrow-line X-ray galaxies detected in ROSAT surveys have X-ray spectra similar to that of Mrk 609 then they should not contribute significantly to the X-ray background.

7 SUMMARY

We have analysed BeppoSAX data of the composite galaxy Mrk 609. The spectrum is described by a power law $\Gamma = 1.6$ with negligible absorption. The absence of absorption is consistent with the small Balmer decrement and the large Ly$\alpha$ flux observed (Rudy et al. 1988). The absence of an obscuring column clearly does not fit the absorbed starburst model proposed by Levenson et al. (2001) to explain the mult wavelength properties of the composite galaxy NGC 6221. The detection of significant soft and hard X-ray variability clearly suggests that the AGN emission dominates the X-ray spectrum. Any starburst contribution to the X-ray emission should be small. In addition, Mrk 609 does not follow the $L_{\text{H}\alpha} - L_{\text{X}}$ correlation of bright AGNs (Ward et al. 1988), showing a weak broad H$\alpha$ component ($\sim 40$ times less than predicted by the X-ray flux). The discrepancy between the optical and X-ray spectra can be explained as a deficit of ultraviolet ionizing photons. This is supported by the SED, which shows no upturn of the spectrum below 3000 Å, implying the absence of an ultraviolet bump. Alternatively, as the optical and X-ray observations were taken 15 years apart, dramatic variability in the X-ray flux could result in a low $L_{\text{H}\alpha} - L_{\text{X}}$ ratio. Finally, the above discrepancy and anomalous line properties could be explained by a small optical depth and ionization parameter in the line-emitting regions.

ACKNOWLEDGMENTS

We thank the referee Dr J. Halpern for useful comments and suggestions, and A. Burston for producing the SED of Mrk 609.

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