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Rapid X-ray variability in the I Zw 1 class object IRAS 13224-3809

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Abstract. X-ray variability in the $0.1 - 2.4keV$ ROSAT energy band with a doubling timescale of 800 s and a factor of 4 within a few hours has been detected in the IRAS AGN 13224-3809. The optical spectrum indicates that IRAS 13224-3809 is a narrow-line Seyfert 1 galaxy with strong permitted Fe II emission, a member of the unusual I Zw 1 class objects. IRAS 13224-3809 appears to be one of the most rapidly variable AGN known so far. This is the first time that variability on a timescale smaller than 1000 s is reported at such high $L(0.1 - 2.4keV) = 3 \cdot 10^{44} erg \cdot s^{-1}$ X-ray luminosity in Seyfert galaxies. It is also the first reported X-ray variability in I Zw 1 class objects. The Δt = 800 s variation indicates that the X-rays come from a compact region of about 17 light minutes in size. Whereas the X-ray emission varies both in the soft S$(0.1 - 0.4keV)$ and in the hard H$(0.4 - 2.4keV)$ band, the hardness ratio (H-S)/(H+S) remains constant implying that no significant spectral changes occur during the X-ray flux variation. The observed steep X-ray spectrum was compared to powerlaw, blackbody and Bremsstrahlung models. Only the Bremsstrahlung model gives an acceptable fit, but it must be rejected on the basis of the variability argument. Emission from a standard accretion disk model fits the data. Again, from the observed rapid variability we are forced to rule out this model. A scenario in which a hard X-ray source irradiates the accretion disk which reemits at soft X-ray energies can explain both, the steep X-ray spectrum and the variability. We speculate that rapid X-ray variability could be a common feature in I Zw 1 type objects and that it may be related to the unusual optical spectra of these sources. This may help to solve the open problem of the $Fe\ II/H_\beta$ ratio in active galactic nuclei.

Key words: galaxies: general – galaxies: active – galaxies: individual: IRAS 13224-3809 – X-rays: galaxies

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1. Introduction

Variability studies are unique tools for studying the physical conditions in astrophysical objects. The timescales on which variability occurs in extragalactic sources give constraints on the sizes of the emitting regions, on the transfer function of the surrounding material, and they can be used to estimate the mass of the central black hole. Usually relativistic beaming is assumed to explain the fast variability in BL Lac objects, first discussed by Blandford & Rees (1978) and Rees (1984). Instabilities in the accretion disk near the central source are supposed to cause the X-ray variability in Seyfert galaxies or QSOs. Most Seyfert galaxies, quasars and BL Lacs show X-ray variability on timescales between 10^4 s and 10^6 s (Feigelson et al. 1986, their Fig. 5; Giommi et al. 1990). Only a few AGN have reported variations on timescales less than about 1000 s. The BL Lac object H0323+022 (Feigelson et al. 1986), perhaps the most rapidly variable extragalactic source known, varies by a factor of 3 in about 30 s. The shortest timescales found in Seyfert galaxies are about 200 s in NGC 6814 and about 1000 s in NGC 4051 and MCG -6-30-15 (Matsuoka et al. 1990).

The ROSAT pointing and optical follow-up observations on IRAS 13224-3809 were motivated by its first X-ray detection in the ROSAT All Sky Survey (Boller et al. 1992). We have speculated that this galaxy is an outstanding object due to its extreme X-ray luminosity of $L_X = 3 \cdot 10^{44} erg \cdot s^{-1}$ and a steep photon index of Γ = 4.4. The 20,000 s ROSAT pointed observation has confirmed the high X-ray luminosity, the steep spectrum and it has additionally revealed the rapid X-ray variability. The results from the ROSAT pointed observation are analyzed in Sect. 2. In Sect. 3 we describe the optical observation. The discussion of the rapid X-ray variability and the spectral analysis for the I Zw 1 class object can be found in Sect. 4.1 to 4.4. As IRAS 13224-3809 shows strong Fe II emission we discuss in Sect. 4.5 and 4.6 the Fe II problem and its links to soft X-rays.

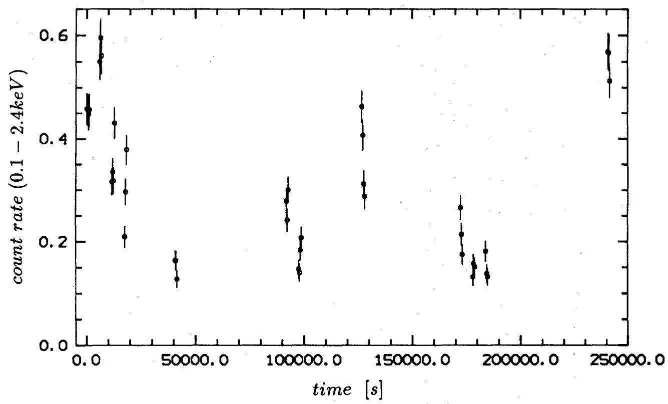

Fig. 1. Count rate versus time for the IRAS galaxy 13224-3809 detected in a 20,000 s ROSAT pointed observation. Large amplitude variations up to a factor of about 4 have been detected on timescales of about 8 hours. Shorter variations are shown in Fig. 2 in the time resolved lightcurve

Table 1. Line intensities and equivalent widths of emission line measurements of IRAS 13224-3809. Column 1 contains the line number as labelled in Fig. 5. The observed wavelengths and the identification of the line are given in columns 2 and 3, respectively. The last two columns give the corresponding line intensities and equivalent widths with an accuracy of about 10%. (1) The line is probably blended

(1) no	(2) $\lambda(obs)$ (Å)	(3) Ion	(4) flux $erg\ cm^{-2}\ s^{-1}$	(5) EW (Å)
1	4765.1	not identified	$1.52 \cdot 10^{-14}$	10
2	4819.2	Fe II 4522.6	$1.88 \cdot 10^{-14}$	12
3	4862.2	Fe II 4555.9	$1.72 \cdot 10^{-14}$	11
4	4890.7	Fe II 4583.0	$8.42 \cdot 10^{-15}$	6
5	4935.9	Fe II 4629.3	$1.92 \cdot 10^{-14}$	13
6	4978.5	not identified	$6.61 \cdot 10^{-15}$	4
7	5183.8	H_β	$3.50 \cdot 10^{-14}$	23
8	5248.2	Fe II 4923.9	$1.24 \cdot 10^{-14}$	8
9	5281.8	[OIII] 4958.9	$5.91 \cdot 10^{-15}$	4
10	5333.3	[OIII] 5006.9	$3.19 \cdot 10^{-14}$	21
11	5471.5	not identified	$5.66 \cdot 10^{-15}$	4
12	5509.0	Fe II 5169.0	$9.29 \cdot 10^{-15}$	6
13	5541.1	Fe II 5197.6	$6.65 \cdot 10^{-15}$	4
14	5584.0	Fe II 5234.6	$8.69 \cdot 10^{-15}$	6
15	5625.2	Fe II 5276.0	$1.31 \cdot 10^{-14}$	9
16	5675.2	Fe II 5316.7(1)	$1.38 \cdot 10^{-14}$	9
17	5721.9	Fe II 5362.9(1)	$6.78 \cdot 10^{-15}$	4

2. X-ray observation

The X-ray observation has been performed between August 10 and August 12, 1992, using the PSPC detector (Pfeffermann et al. 1987) on the ROSAT satellite (Trümper 1983) in a 20,000 s pointing on IRAS 13224-3809. The mean count rate in the ROSAT $0.1 - 2.4 keV$ energy band is 0.31 $counts \cdot s^{-1}$. The resulting X-ray luminosity is $3 \cdot 10^{44} erg \cdot s^{-1}$ assuming Galactic column density of $4.85 \cdot 10^{20} cm^{-2}$ and a photon index of 4.4 (see Sect. 4 for details).

Figure 1 shows the X-ray $(0.1 - 2.4 keV)$ lightcurve of IRAS 13224-3809. The count rates vary between 0.127 and 0.594 $counts \cdot s^{-1}$. The data are binned in 400 s time intervals suggested by the wobble period of the telescope during the pointing. The observation is split into several individual pointings. Amplitude variations of a factor of about 4 can be seen on timescales between 8 and 16 hours. The finer resolved X-ray lightcurve of Fig. 2 shows coherent variations on timescales of about 800 s by a factor of 2 between epochs at 18,000 and at 128,000 s after the beginning of the observation. Many more interesting features indicating even shorter variations by some 20% can be seen, of course, with less statistical significance.

3. Optical observations

A CCD image of IRAS 13224-3809 and two long-slit spectra were taken with the La Silla 3.6 m telescope using the EFOSC spectrograph on December 24, 1992. The detector was a Tektronix 512x512 pixel CCD (Tek # 26), of pixel size 0.607 arcsec, read-out noise 8.4 electrons, and gain 4 e/ADU. Each spectrum was exposed 5 minutes. The slit has a length of 3.6 arcmin, and a width of 1.5 arcsec. It was aligned along a direction passing the galaxy nucleus and the compact object seen at about 7 arcsec (west) of the nucleus. The wavelength of grism B300 ranges from 3733 to 6915 Å. The resolution of 2.35 pixels = 14.8 Å was determined from the FWHM of the emission lines of the calibration He-Ne-Ar arc spectra. The spectrophotometric standard star LTT 2415 was observed at an airmass of 1.33 to calibrate the flux of the object spectra observed at the same airmass. The IRAF package was used for data reduction and analysis. Figure 3 shows the final co-added spectrum, unsmoothed and flux-calibrated. The wavelength accuracy of 0.7 Å was checked using the sky background spectrum of solar absorption lines. Numerous emission lines are seen in the galaxy spectrum. The Fe II lines from the multiplets around 4570 and 5270 Å, H_β and $[OIII]\lambda\lambda5007$, relevant to the present study, were measured. The intensity of the narrow H_β emission is only slightly broader than the forbidden line [O III] $\lambda\lambda$5007. No indications for broad wings of H_β are apparant.

CCD images and spectra were again obtained on IRAS 13224-3809 at La Silla with the 2.2 m telescope using the EFOSC2 spectrometer on the nights of january, 16th and january, 17th 1993. Figure 4 shows the optical spectrum taken on january, 16th. The projected slit-width was 8 Å sampled by 3 pixels. The reductions were done on the standard way similar to the one described above. No significant changes, neither in the strong emission-line widths nor in the $FeII\lambda\lambda4570/H_\beta$ ratios can be detected from one night to the next with our signal to noise ratio. The line intensities are in good agreement with those given in Table 1. Another spectrum centered further in the blue was also obtained under poor conditions during the night of january, 20th and does not show differences either.

Figure 5 shows for the blue spectrum (Fig. 3) the results from a multiple-line profile fitting with deblending of the Fe

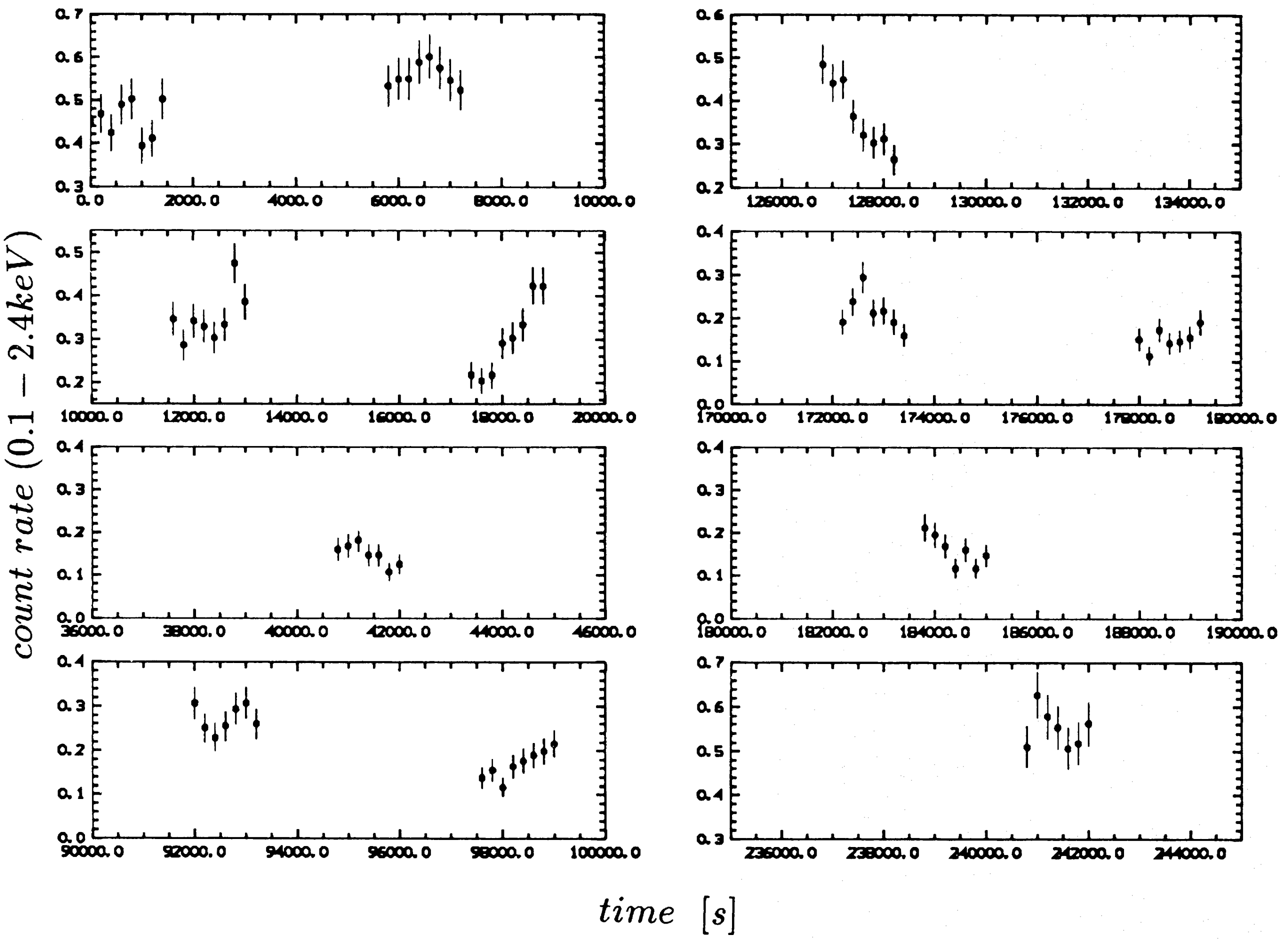

Fig. 2. Time resolved lightcurve. The binsize is 200 s

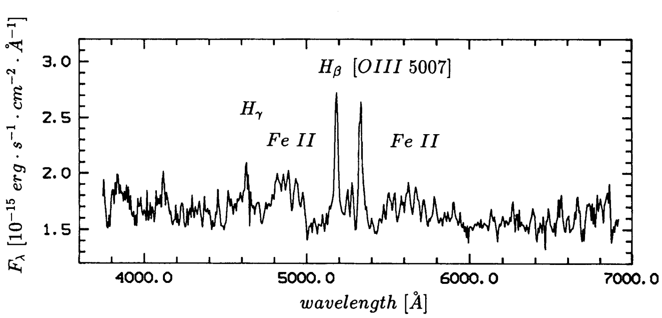

Fig. 3. Optical spectrum of IRAS 13224-3809 obtained at the 3.6 m telescope at La Silla in December, 1992

II complexes. Table 1 contains line intensities and equivalent widths for the emission lines detected in the optical spectrum. The line widths determined from the red spectrum (Fig. 4) is about 650 $km \cdot s^{-1}$ for H_β, equal or slightly smaller than the widths of the $[OIII]\lambda\lambda5007$ line. For the intensity ratio of $[OIII]\lambda\lambda5007/H_\beta$ we find 0.9, a level below the limit 3 which together with the line widths and the presence of Fe II classifies IRAS 13224-3809 as a narrow-line Seyfert 1 galaxy (Osterbrock & Pogge 1985). For the intensity ratio of H_α/H_β we find a value of 7.6. The total intensity of the Fe II multiplet group at $\lambda\lambda4570$ was measured. Assuming that the lines 1 to 6 (Table 1) belong to this group we find a ratio of $FeII\lambda\lambda4570/H_\beta$ = 2.4. Following Joly (1991), AGN with $FeII\lambda\lambda4570/H_\beta > 0.5$ are called "strong Fe II emitters", AGN with $FeII\lambda\lambda4570/H_\beta < 0.5$ are called "weak Fe II emitters". The median value of the distribution of the $FeII\lambda\lambda4570/H_\beta$ ratio is about 0.5 for her sample of about 200 AGN with collected Fe II data. The corresponding ratio for the other narrow-line Seyfert 1 galaxies with strong Fe II emission is 0.99 for Mrk 42, 1.31 for Mrk 493, 1.34 for I Zw 1 and 2.71 for Mrk 507.

The strong Fe II blends together with the classification as narrow-line Seyfert 1 galaxy accounts for the categorization of IRAS 13224-3809 as a I Zw 1 object. As all I Zw 1 objects, IRAS 13224-3809 shows a strong IR continuum with a far-infrared luminosity $L(40-120\mu m)$ of about $1.5 \cdot 10^{45} erg \cdot s^{-1}$ (Boller et al. 1992, Table 1a).

4. Discussion

4.1. General considerations

The $\Delta t \simeq 800$ s X-ray variations with $\Delta L = 1.5 \cdot 10^{44} erg \cdot s^{-1}$ indicate that the X-rays come from a compact region of about

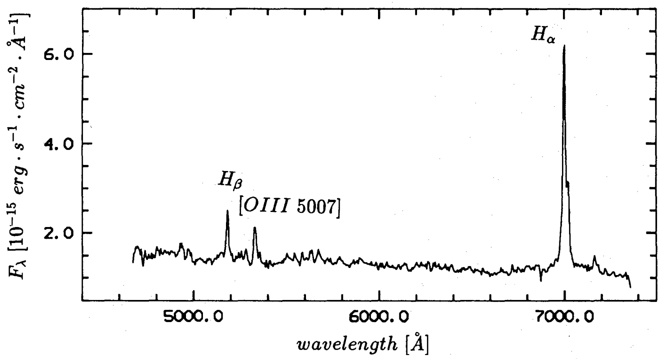

Fig. 4. Optical spectrum of IRAS 13224-3809 obtained at the 2.2 m telescope at La Silla in January, 1993

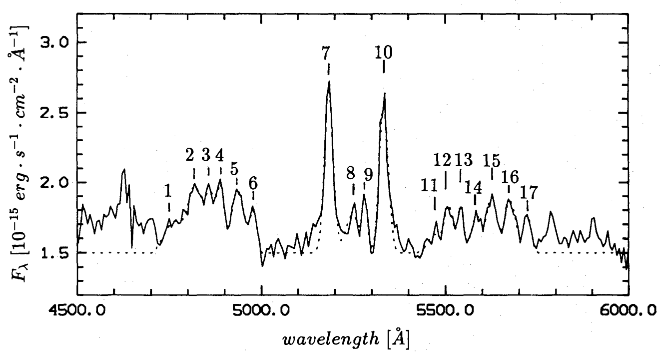

Fig. 5. Multiple line fit with line deblending of the Fe II complexes around $\lambda\lambda$4570 and $\lambda\lambda$5190 and $\lambda\lambda$5320 for the optical spectrum of IRAS 13224-3809 shown in Fig. 3. The dashed line indicates the results from the fit

$R \simeq \Delta t\ c \approx 10^{-5} pc$ in size which must be located close to the central black hole, say at a distance $R \leq 5\ R_S$, where R_S is the Schwarzschild radius. The upper limit for the black hole mass resulting from the time variability constraint is

$$M \leq 1.6 \cdot 10^7\ M_\odot \quad (1)$$

This corresponds to

$$L_{edd} \leq 2.1 \cdot 10^{45}\ erg/s \quad (2)$$

which means that

$$L/L_{edd} \geq 0.13. \quad (3)$$

In Eq. (3) the $(0.1 - 2.4 keV)$ luminosity is used as a lower limit for the bolometric luminosity resulting from the spectral energy distribution of an accretion disk. Therefore, the value of 0.13 given in Eq. (3) has to be considered as a lower limit for the accretion rate.

A direct consequence of intrinsic variability on such short timescales is that most of the X-ray emission must be seen directly from the emitting regions without X-ray scattering. Any X-ray scattering by electron clouds, supposed to have sizes of light days or larger, would smear out the short time scale.

Table 2. X-ray spectral fits for power law, blackbody, bremsstrahlung and modified thin disk (Shakura & Synyaev 1973) models. N_H is in units of $10^{20} cm^{-2}$. The normalization is given in units of $photons \cdot cm^{-2} \cdot s^{-1} \cdot keV^{-1}$ at 1 keV. The accretion rate in the thin disk model is in units of the Eddington rate. Confidence intervals are 90% confidence intervals

Powerlaw model with N_H free	
$N_H(10^{20})$	$8.74_{8.20}^{9.28}$
Photon Index	$4.40_{4.24}^{4.56}$
Normalization	$9.19 \cdot 10^{-4}$
χ^2	4.3 for 16 d.o.f
Blackbody model with N_H fixed at the galactic value	
$N_H(10^{20})$	4.80
Temperature kT(keV)	$1.03_{1.02}^{1.05} \cdot 10^{-1}$
Normalization	$5.59 \cdot 10^{-4}$
χ^2	26.0 for 17 d.o.f.
Blackbody model with N_H free	
$N_H(10^{20})$	$1.57_{1.33}^{1.84}$
Temperature kT(keV)	$1.40_{1.35}^{1.44} \cdot 10^{-1}$
Normalization	$8.82 \cdot 10^{-4}$
χ^2	2.6 for 16 d.o.f.
Bremsstrahlung model with N_H free	
$N_H(10^{20})$	$4.71_{4.40}^{5.04}$
Temperature kT(keV)	$3.00 \cdot 10^{-1}$
Normalization	$9.18 \cdot 10^{-4}$
χ^2	1.0 for 16 d.o.f.
Disk with N_H free, viscosity parameter α fixed to 0.1	
$N_H(10^{20})$	$4.23_{3.90}^{4.58}$
accretion rate	$0.66_{0.64}^{0.68}$
central mass($10^6 M_\odot$)	$3.79_{3.22}^{4.30}$
Normalization	$8.96 \cdot 10^{-4}$
χ^2	1.0 for 15 d.o.f.

4.2. Temporal behaviour and spectral variability

The hardness ratio lightcurve in Fig. 6 c has been computed from the lightcurves seen in the soft S$(0.1 - 0.4 keV)$ (Fig. 6a) and hard H$(0.4 - 2.4 keV)$ (Fig. 6b) ROSAT energy bands assuming that it is defined by (H-S)/(H+S). The soft lightcurve follows the behaviour of the hard lightcurve qualitatively. If a grey absorber crosses the line of sight, then one should expect that the absorption at soft X-rays is larger than that at hard X-rays. X-ray lightcurve and X-ray hardness ratio lightcurve should be anticorrelated. No significant variation of the hardness ratio lightcurve is found. We conclude that if absorption occurs along the line of sight then it has to be a partial absorber. The column density of neutral hydrogen in such clouds should then be larger than about $10^{23} cm^{-2}$. In this scenario X-rays are totally shadowed by such clouds, but not intrinsically absorbed at soft X-rays. We conclude from the constant hardness ratio

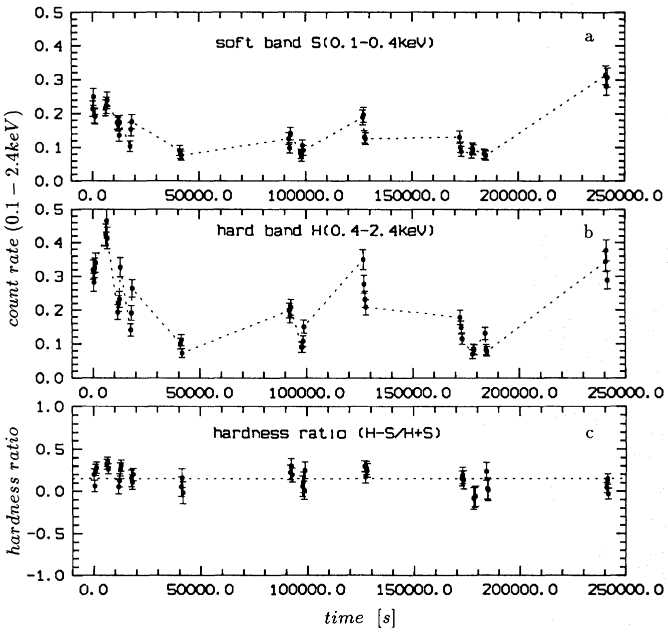

Fig. 6. X-ray lightcurves in the soft and hard ROSAT energy band and the resulting hardness ratio lightcurve. Grey absorption of clouds along the line of sight would produce a variation in the HR-lightcurve which should be anticorrelated to the X-ray lightcurve. The HR lightcurve shows no significant variation

lightcurve that no grey absorbers cross the line of sight towards IRAS 13224-3809.

4.3. Results from spectral analysis

From the analysis of the hardness ratio lightcurves we determined that no strong spectral variations occurred. Therefore, we produced a single pulse height spectrum of the source. Data preparation was performed in the standard fashion within the EXSAS analysis system (Zimmermann et al. 1992). The observed spectrum was compared to various standard models using version 7.1 of the XSPEC program (Shafer et al. 1991). A summary of the derived best fits is presented in Table 2.

An absorbed power law model fits the data rather poorly (χ^2_{red} = 4.3).

An absorbed Bremsstrahlung model yields an acceptable fit. The best fitting N_H value is consistent with the one derived from the HI radio maps. The spectral parameters of the model are listed in Table 2. From the light travel time argument we know that the source cannot exceed the size of $R_{max} \simeq 3 \times 10^{13}$ cm. Making use of the relationship $L \propto n^2 T^{1/2} V$, where L is the luminosity, n is the number density, T the temperature, and V the volume of the emitting region, we determine a lower limit for the gas density in the source of $n = 2.4 \times 10^{13}$ cm^{-3}. This implies a minimum column density of $n \cdot R_{max} = 7.3 \times 10^{26}$ cm^{-2}, clearly in contradiction with the assumption that the source is optically thin.

An absorbed blackbody model, with the column density N_H fixed to the value determined from 21 cm radio maps, $4.8 \times 10^{20} cm^{-2}$ (Dickey & Lockman 1990), also yields very poor results (χ^2_{red} = 26). Leaving in that model the N_H free we find a best fitting value of $1.57 \times 10^{20} cm^{-2}$, which is significantly smaller than the Galactic value, note that χ^2_{red} is still unacceptable large.

From the fact that the blackbody model does not fit the data we infer that the observed spectrum should come from an emitting region characterized by a distribution of temperatures.

Therefore, all indications are consistent with emission from an accretion disk. We have therefore tested this possibility by comparing the data with the thin accretion disk model of Shakura & Synyaev (1973) available within the XSPEC program. The model yields an acceptable fit to the data; the derived N_H is somewhat smaller than the one determined from radio maps, $N_H = 4.3^{4.58}_{3.90} \cdot 10^{20} cm^{-2}$. Having determined the accretion disk parameters we can compute the characteristic timescales of the disk. The fastest timescales are the thermal timescale, $t_{th} = 4/3\alpha^{-1}\omega^{-1}$, and the sonic timescale, $t_s = r/\omega h$. The thermal timescale is the timescale on which thermal instabilities grow, the sonic timescale is that one on which sound waves cross the disk. α is the viscosity parameter (cf. Shakura & Synyaev 1973), ω is the angular velocity and h is the scale height of the disk. We have tried different values of α in the range 0.01 to 1 and found that the shortest timescales, at $R = 5R_s$, are respectively t_{th} = 1900 s and t_s = 2300 s.

These timescales are a factor of two larger than the observed doubling timescale. Note also that these values should be considered as lower limits for the doubling timescales that can be obtained from a disk. A 100% variation in the luminosity can be produced only if a substantial fraction of the disk is involved (from $\simeq 3R_S$ to $\simeq 25R_S$), where the timescales are longer. We conclude that as for the bremsstrahlung model, the accretion disk model can reproduce the observed spectrum but probably cannot explain the fast variability. Therefore other models like irradiation models have to be considered.

Analysis of GINGA data for a sample of Seyfert 1 galaxies (eg. Pounds et al. 1990) has lead to the widely accepted picture of a compact hard X-ray source irradiating a 'cold disk' (e.g. George & Fabian 1991). This model is characterized by a spectrum which is similar to the standard disk spectrum. The variability timescales, however, can be considerably shorter as they arise from variations in the hard X-ray source. This model can explain the X-ray observations of IRAS 13224-3809. A shortcoming of the model is that it requires a hard X-ray component which is not observed in the PSPC spectrum. The $0.1 - 2.4 keV$ spectrum of IRAS 13224-3809 lacks the hard component commonly observed in the PSPC spectrum of the Seyfert 1 galaxy MKN 766 (Molendi et al. 1993) or NGC 5548 (Nandra et al. 1992). A possible explanation is that the hard X-ray component does not extend to the soft X-ray energies or is not visible to ROSAT.

4.4. Searching for spectral variability

Flux variations in the thermal models described in Sect. 4.3 are likely connected with temperature variations.

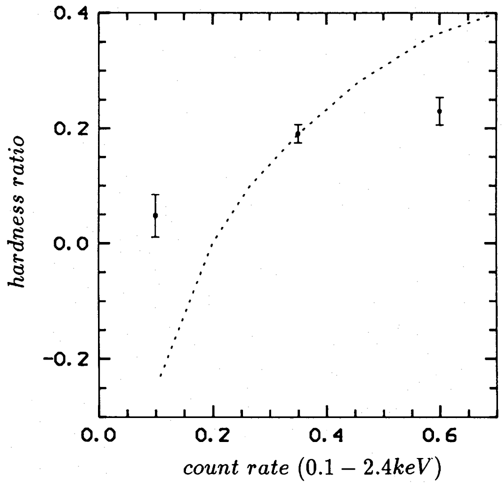

Fig. 7. The hardness ratio of IRAS 13224-3809 in dependence of low (*count rate* < 0.2), medium (*count rate* $= 0.2 - 0.5$) and high (*count rate* > 0.5) state of the X-ray lightcurve (cf. Fig. 1.). Due to the increased statistics by summing up the observation for intervals in the count rate, small variations in the hardness ratio can be determined. Confidence intervals are 90 % confidence intervals. The dashed line represents the expected values for the count rate and the hardness ratio assuming a one-temperature medium ($L \sim T^4$)

Temperature variations will of course result in spectral variations in the sense that a temperature increase will produce both a count rate increase and a hardening of the spectrum. Since we have no indication of strong spectral variations from the hardness ratio lightcurve we have decided to investigate small spectral variations by dividing our dataset into 3 subsamples, a low count rate, i.e. $< 0.2\ counts \cdot s^{-1}$, medium count rate, i.e. $0.2 - 0.5\ counts \cdot s^{-1}$ and a high count rate, i.e. $> 0.5\ counts \cdot s^{-1}$ sample and computing the respective hardness ratios. As can be seen in Fig. 7 the hardness ratio for the low state is significantly smaller than the hardness ratio for the high state. Note that results from Fig. 7 confirm our previous statement (Sect. 4.2) that variability does not result from grey absorbers crossing the line of sight. In such a case the hardness ratio would be anticorrelated, with the count rate.

We also note that a relatively small increase in the hardness ratio with count rate is consistent with the picture of optically thick thermal emission. In such a case, the luminosity is correlated to the temperature of the emitting material. Assuming a one-temperature medium ($L \sim T^4$) a small increase of the temperature will result in small increase of the hardness ratio and a large increase of the observed flux. The dashed curve in Fig. 7 represents the expected values for the count rate and hardness ratio assuming blackbody emission. The temperature ranges from 0.08 (lower left corner) to 0.12 (upper right corner) keV. The dashed line follows the trend of increasing hardness ratio with increasing count rate. It is also obvious that a one-temperature medium does not fit the observed dependence in Fig. 7. We infer that the emitting region is characterized by a distribution of temperatures.

4.5. Discussion of the Fe II problem

Fe II emission is supposed to arise in the broad-line high density region ($N_e \geq 10^8 cm^{-3}$, Wampler & Oke 1967, Osterbrock 1978, Blandford et al. 1990). The presence of Fe II in the spectrum indicates an electron temperature of $T_e \leq 4 \cdot 10^4 K$, as for higher temperatures it would be nearly completely collisionally ionized to Fe III. The main optical Fe II multiplets are at around $\lambda\lambda 4570, 5190, 5320$. Fe II has an extremely complicated energy-level diagram arising from radiative transitions from the excited levels of odd parity with energies of $\sim 5eV$ to lower even levels. Theoretical calculations of the Fe II emission and a comparison with the observations can be found in Wills et al. (1985).

The broad-line regions (BLR) emitting Fe II lines are thought to be heated and ionized by hard X-ray photons. X-rays penetrate deep into the clouds creating a warm, partially ionized zone at high optical depths where low ionization lines, such as Fe II emission, are generated. Halpern & Oke (1987) have shown that the X-ray luminosity of narrow-line Seyfert 1 galaxies with strong Fe II lines is higher than that of Seyfert 2 galaxies but of the same order of normal Seyfert 1's. They have speculated that the existence of I Zw 1 objects implies that X-ray emission is a necessary condition for the excitation of Fe II emission. The X-ray luminosity of a few $10^{44} erg \cdot s^{-1}$ in IRAS 13224-3809 supports the relation between X-ray luminosity and Fe II emission.

The relation between the optical Fe II emission and soft X-rays has been investigated in several papers. Photoionization models of the BLR clouds indicate that the strength of the optical Fe II emission is related to the number of hard X-ray photons (Collin-Souffrin et al. 1988, Joly 1987). Wilkes et al. (1987) proposed a correlation between the strength of the optical Fe II emission and the soft X-ray slope. However, the correlation is opposite to the expected relationship arising from theoretical models. Boronson (1989) has called in question the relationship of Wilkes et al. by analysing a larger sample of 15 quasars. They concluded that a correlation between the strengths of Fe II emission and the soft X-ray slope is not existent. Also Zheng & O'Brien (1990) found that a such a relation is not present in their sample of 33 QSOs, including the sample of Wilkes et al. Recently, Walter & Fink (1993) have investigated the ultraviolet to soft X-ray bump for 58 Seyfert 1 type galaxies using the X-ray spectra obtained during the ROSAT All Sky Survey. For 22 of their sources optical Fe II measurements can be found in the paper by Joly (1991). Similar to the results found by Boronson (1989) and Zheng & O'Brien (1990) there is no correlation between the slope of the soft X-ray emission and the optical Fe II emission present.

The Fe II problem is an unsolved problem in AGN studies. From observations it is known that the total strength of the Fe II blends can equal the H_α intensity (Collin-Souffrin et al. 1986) while the strength calculated from photoionization models is only about 0.5 (Collin-Souffrin et al. 1986 and references therein).

There are several explanations for the Fe II problem. Collin-Souffrin and collaborators (1988) have shown that the observed $Fe\,II/H_\alpha$ ratio may result from hard X-ray reprocessing in *the outer region* of the accretion disk, where physical conditions are different from those of normal broad-line region clouds, i.e. the gas is in hydrostatic equilibrium and the density is higher. Such conditions selectively increase $FeII$ emission with respect to balmer line emission. It is of some interest that our spectral analysis of the PSPC data leads to a similar scenario, namely that IRAS 13224-3809 may host a hard X-ray source which irradiates the disk. The assumptions of Collin-Souffrin et al. (1988) solve the Fe II problem in the majority of AGN. The Fe II problem is however not completely solved in the case of intense Fe II emitters with $FeII\lambda\lambda 4570/H_\beta > 0.8$ (Joly 1988, her Fig. 4). Other possible explanations include a non-radiatively heated medium which is emitting mainly the optical Fe II multiplets or overabundance of iron in the BLR (Collin-Souffrin et al. 1982, Joly 1987). The assumptions of Collin-Souffrin and collaborators (1988), that the Fe II emission arises under special physical conditions and geometrical structure, is supported by the strong trend found by Zheng and O'Brien (1990) that QSOs with broader H_β lines have weak or absent optical Fe II emission (their Fig. 2). Zheng & O'Brien argue that this relation may be understood, if the Fe II line emission is formed in a special zone and if it has a stronger aspect dependence than the underlying optical continuum. Our observations of H_β and Fe II are consistent with this interpretation. If these lines have the same aspect dependence, one would see no Fe II - H_β relation.

In narrow-line Seyfert 1 galaxies with Fe II emission, additionally to the Fe II problem, the absence of broad wings in the H I lines has to be explained. One possible explanation for the absence of broad H I wings in narrow-line Seyfert 1 galaxies could be that we observe in these galaxies only a part of the BLR, far from the center, while the bulk of the region, which emits the wings, is hidden like the BLR in some Seyfert 2 galaxies. This could explain the relative narrow H I lines and the the presence of Fe II emission in narrow-line Seyfert 1 galaxies with Fe II emission, both supposed to be mainly arising from outer parts of the nuclear core region. The high H_α/H_β ratio found in our object supports this interpretation.

The conventional explanation for the nature of narrow-line Seyfert 1 galaxies, as described by Osterbrock & Pogge (1985), namely the existence of an AGN in the centre, was based essentially on the presence of Fe II lines (only seen in QSOs and classical Seyfert 1 galaxies) and the line widths larger than what was observed in "HII type" galaxies. Recent studies have however shown on one hand, that the Fe II lines could be produced by shocks in strong starformation regions (Lipari et al. 1993) and on the other hand, that luminous IRAS galaxies are often the result of mergers, so that line widths of a few hundred $km \cdot s^{-1}$ are not exceptional anymore. If one adds the strong reddening often seen in IRAS galaxies, the parameters used to define narrow-line Seyfert 1 galaxies could be produced all by starformation. The key-characteristic to identify a hidden AGN is therefore the X-ray variability which is hard to reproduce with starformation models at such high X-ray luminosities and rapid time scales. The observations of IRAS 13224-3809 presented here seem therefore a strong support for the presence of an AGN in narrow-line Seyfert 1 galaxies.

4.6. Suggestive links between rapid X-ray variability and narrow H I lines in IRAS 13224-3809

The combination of unusual observational parameters, the rapid X-ray variability, the steep X-ray spectrum, and the extreme $Fe\ II/H_\beta$ ratio has brought us to search for possible links between these parameters in IRAS 13224-3809. We want to add another speculative explanation for the existence of narrow HI lines and pronounced optical Fe II emission in IRAS 13224-3809. In our speculation we may suppose that the normal BLR which emits the wings of the HI lines is disturbed by the outflow of gas and dust from the central source. We have indications that in IRAS 13224-3809 super-Eddington conditions may be reached, which could lead to fast variability and may change the conditions in the broad-line region. The size of the emitting region can also be estimated from spectral models. If we assume optically thick emission, the size is considerably smaller than the upper limit, R_{max}, derived in Sect. 4.1. The smallest possible size is derived by assuming the most efficient emission mechanism, i.e. blackbody emission. From the blackbody fit reported in Table 2 we derive a minimum size for the emitting region of about $2.5 \cdot 10^{11} cm$. Proceeding as in Sect. 4.1. we estimate a lower limit of the black hole mass of $M \geq 1.6 \cdot 10^5 M_\odot$ and a lower limit of the Eddington luminosity of $L_{edd} \geq 2.3 \cdot 10^{43} erg \cdot s^{-1}$. We obtain $0.1 < L/L_{edd} < 10$. From the standard disk model fit we have $L/L_{edd} \simeq 0.7$, which is close to the Eddington limit, too. Therefore it seems that IRAS 13224-3809 may be accreting at a super-Eddington rate. Under super-Eddington conditions the broad line region may be affected by outflow of gas and dust from the central source depressing the broad balmer line emission. As mentioned above Fe II could arise mainly from the outer regions of the disk and would therefore not be influenced strongly by the outflow.

We may suppose that a search for rapid variability in other I Zw 1 objects could be interesting to find out whether this is a common feature in this object class. Such a relation would offer additional constraints to theoretical models which may also be helpful in solving the general problem of the Fe II emission detected in AGN. Awaki (1992) has found rapid time variability with the shortest doubling timescale of about 1500 s in IRAS 18325-5926 (his Fig. 5-15). This timescale is about a factor of 2 larger than that found in IRAS 13224-3809, but indicates that IRAS 18325-5926 belongs to the fastest X-ray variable Seyfert galaxies. It also resembles to IRAS 13224-3809 that the spectral shape of IRAS 18325-5926 does not change significantly and that the spectrum is steep. Awaki gives a Seyfert 2 classification for IRAS 18325-5926. Inspection of the optical spectrum presented by Carter (1984) shows some emission between $\lambda\lambda$ 5190-5320, situated at the very edge of the spectrum. The identification as Fe II emission has to be taken with caution as this feature should be correlated with the Fe II emission at $\lambda\lambda$ 4570 which is weak or absent. On the other hand, none of the other objects classified by Carter as Seyfert 2s show such a strong emission at the edge of their spectra. Optical follow-up observation of IRAS 18325-5926 is required to find out if this object could be also a I Zw 1 class object showing rapid X-ray variability.

In this paper we report on rapid X-ray variability in a narrow-line Seyfert 1 galaxy with optical Fe II emission. Our results from the X-ray spectral analysis favour a scenario in which a hard X-ray source irradiates the accretion disk which reemits at soft X-ray energies. Following Collin-Souffrin (1988) a hard X-ray source is a necessary condition for the optical Fe II emission supposed to arise from outer regions of an accretion disk. The absence of broad H I wings can be explained if only a part of the BLR, far from the center, is observed and the bulk of the region, which emits the wings, is hidden. We want to draw attention to the fact that rapid X-ray variability could also be connected with the absence of broad H I lines in IRAS 13224-3809. Further work is of course necessary to clarify the interesting link between the optical properties of the I Zw 1 object IRAS 13224-3809 and the X-ray variability reported in this paper.

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References

Awaki, H. 1992, "X-ray study of Seyfert galaxies, and the unified theory, thesis, ISAS research note **473**
Blandford, R.D., Rees, M. 1978, Pittsburgh Conference on Bl Lac Objects, ed. A.M. Wolfe, Univ. Pittsburg Press, Pittsburgh, p. 328.
Blandford, R.D., Netzer H., Woltjer, L. 1990, Active Galactic Nuclei, Lecture Notes 1990, Swiss Society for Astrophysics and Astronomy, ed. Courvoisier, T.J.-L., Mayor, M.
Boller, Th., Meurs, E.J.A., Brinkmann, W., Fink, H., Zimmermann, Adorf, H.-M., A&A, 1992, **261**, 57.
Boroson, T.A., ApJ, 1989, **343**, L9.
Carter, D., Astronomy Express 1984, **1:2**, 61.
Collin-Souffrin, S., Dumont, S., Tully, J., A&A 1982, **106**, 362.
Collin-Souffrin, S., Dumont, S., Joly, M., Pequignot, D., A&A 1986, **166**, 27
Collin-Souffrin, S., Hameury, J.-M., Joly, M., A&A 1988, **205**, 19
Dickey, J. M., and Lockman, F. J. 1990, ARA&A, 28:215-61.
Dumont, A.M. and Collin-Souffrin, S., A&A 1990, **229**, 302.
Feigelson, E.D. et al., ApJ, 1986, **302**,337.
George, I.M, Fabian, A.C., MNRAS 1991, **249**, 352.
Giommi, P., Barr, P., Garilli, B., Maccagni, D., Pollock, A.M.T., ApJ 1990, **356**, 432.
Goodrich, R.,W., ApJ 1989, **342**, 224.
Halpern, J.P and Oke J.B., ApJ 1987, **312**, 91.
Joly, M., A&A 1991, **242**, 49.
Joly, M., A&A 1987, **184**, 33.
Lipari, S., Terlevich, R., Macchetto, F., ApJ 1993, **406**, 451.
Matsuoka, M., Piro, L, Yamauchi, M., ApJ 1990, **361**, 440.
Mittaz, J.P.D. and Branduardi-Raymont, G., MNRAS 1989, **238**, 1029
Molendi, S., Maccacaro, T., Schaeidt, A&A 1993, **271**, 18.
Nandra, K. et al., accepted for publication in MNRAS 1992.
Osterbrock, D.E, Pogge, R.W., ApJ 1985, **297**, 166.
Osterbrock, D.E., Physica Scripta 1978, **17**, 285.
Pfeffermann, E., Briel, U.G., Hippmann, H., Kettenring, G., Metzner, G., Predehl, P., Reger, G., Stephan, K.-H. 1987, MPE print **81**.
Pounds, K.A, Nandra, K., Steward, G.C., George, I.M., Fabian, A.C., Nat 1990, **344**, 132
Rees, M. 1984, ARA&A, **22**, 471
Shakura, N.I., Synyaev, R.A., A&A 1973, **24**, 337.
Shafer, R.A., Haberl, F., Arnaud, K.A., Tennant, A.F., XSEPC Users Guide 1991 ESA TM-09
Trümper, J. 1983, Adv. Space Res. **4**, 241.
Walter, R. and Fink, H. 1993, MPE Preprint **251**.
Wampler, E.J. and Oke, J.B., ApJ 1967, **148**, 695.
Wilkes, B.J., Elvis, M., McHardy, I., ApJ 1987, **321**, L23.
Wills, B.J., Netzer, H., Wills, D., ApJ 1985, **288**, 94.
Zheng, W., O'Brien, P.T., ApJ 1990, **353**, 433.
Zimmermann, H.U., Belloni, T., Izzo, C., Kahabka, P., Schwentker, O., MPE Report **48**, 1992

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