The giant X-ray outbursts from nearby, non-active galaxies: tidal disruption flares?

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Abstract. One efficient method to probe the direct vicinity of SMBHs in nearby galaxies is to make use of the detection of flares from tidally disrupted stars (e.g., Lidskii & Ozernoi 1979, Rees 1988). The first few excellent candidates for the occurrence of this process in non-active galaxies have emerged recently. Here, we present a review of these observations, compare with variability in AGN, and discuss theoretical implications. We concentrate on the cases of NGC 5905 and RXJ1242-1119, and report results from a systematic search for further X-ray flares from a sample of >100 nearby galaxies.

1. Introduction
There is strong evidence for massive dark objects at the centers of many galaxies. Observations of the dynamics of stars have been used to derive constraints on the mass of the nucleus. An alternative approach to probe the conditions in the nuclear region, and to detect supermassive black holes (SMBHs) if they are there was suggested by Lidskii & Ozernoi (1979) and Rees (1988). They proposed to look for these SMBHs based on the flare of electromagnetic radiation, emitted by a star when it is tidally disrupted and accreted by the black hole. The first good candidates of these kind of events have been reported in the last few years.

2. X-ray variability of AGN
Many active galactic nuclei (AGN) are variable in X-rays with a range of amplitudes and on many different timescales (e.g., Mushotzky et al. 1993). The cause of variability is usually linked in some way or the other to the central engine; e.g., by changes in the accretion disk.

The source’s variability behavior provides important information on the emission mechanisms, the size and geometry of the central region, and the physical conditions in the illuminated circum-nuclear gas like the broad line region and the warm absorber.

Whereas X-ray variability by factors of about 2 – 3 is a common property of AGN, X-ray outbursts by factors of order 50 or more are extremely rare; only very few objects have been reported to show such behavior. Among these are E1615+061 (Piro et al. 1988) and IRAS 13224 with its repeated X-ray outbursts (Otani et al. 1996, Boller et al. 1997). Different mechanisms to account for the X-ray variability have been favored for these galaxies: a variable soft excess for E1615+061 (Piro et al. 1988, see also Piro et al. 1997), relativistic effects in the accretion disk for IRAS 13224 (Boller et al. 1997). The Narrow-line Seyfert 1 galaxy RXJ0134-4258 underwent a dramatic spectral change from ultra-soft to flat within 2 years, corresponding to huge X-ray variability in the hard band. The cause of this peculiar behavior is presently unclear. The model that has been studied in most detail so far is the presence of a time-variable warm absorber (Komossa & Meerschweinchen 2000, and references therein).

Tab. 1 gives some examples of large-amplitude variability (factors of 10 or more) of active galaxies. The list is not complete, but shows that large-amplitude variability occurs in all types of AGN. In addition, among those with the largest factors of variability are some galaxies which are not active at all; these will be discussed in more detail in the next sections of this contribution.

3. Flares from tidally disrupted stars
Questions of particular interest in the context of AGN evolution are: what fraction of galaxies have passed through an active phase, and how many now have non-accreting and hence unseen SMBHs at their centers (e.g., Rees 1989)?

Several approaches were followed to study these questions. Much effort has concentrated on deriving central object masses from studies of the dynamics of stars and gas in the nuclei of nearby galaxies. Earlier ground-based evidence for central quiescent dark masses in non-active galaxies (e.g., Tonry 1987, Dressler & Richstone 1988, Kormendy & Richstone 1992) has been strengthened by recent HST results (e.g., van der Marel et al. 1997, Kormendy et al. 1996; see Kormendy & Richstone 1995 for a...
Table 1. Examples of large-amplitude X-ray variability in galaxies/AGN, excluding BL Lac objects.

| object      | type  | observatories        | references               | factor of variability |
|-------------|-------|----------------------|--------------------------|-----------------------|
| NGC 3786    | Sy 1.8 | ROSAT                | Komossa & Fink 1997a     | 10                    |
| NGC 3227    | Sy 1.5 | ROSAT                | Komossa & Fink 1997b     | 15                    |
| PG 1211+143 | QSO   | EXOSAT → ASCA        | Yaqoob et al. 1994       | 16                    |
| PHL 1092    | NLQSO | Einstein → ROSAT     | Forster & Halpern 1996   | 20                    |
| NGC 4051    | NL  | BeppoSAX → ROSAT     | Guainazzi et al. 1998    | 30                    |
| IRAS 13224  | NLSy 1.8 | ASCA  | Komossa & Greiner 1999b | 30                    |
| 1E 1615     | Sy 1  | HEAO I → EXOSAT      | Piro et al. 1988         | 10-100                |
| IC 3599     | Sy 1.9 | ROSAT                | Brandt et al. 1995,     | 70                    |
| = Zw 159.034|       |                      | Grupe et al. 1995; Komossa & Bade 1999 | 200                  |
| NGC 5905    | HII   | ROSAT                | Bade et al. 1996, Komossa & Bade 1999 | 200                  |
| RXJ 1624+7554 | no emi. lines | ROSAT | Grupe et al. 1999 | 200                  |
| RXJ 1242−1119 | no emi. lines | ROSAT | Komossa & Greiner 1999 | > 20                  |

* classification based on optical spectra

review). There is now excellent evidence for a SMBH in our galactic center as well (Eckart & Genzel 1996).

On the other hand, X-rays trace the very vicinity of the SMBH. Lidskii & Ozernoi (1979) and Rees (1988, 1990) suggested to use the flare of electromagnetic radiation predicted when a star is tidally disrupted and accreted by a SMBH as a means to detect SMBHs in nearby non-active galaxies.

Depending on its trajectory, a star gets tidally disrupted after passing a certain distance to the black hole (e.g., Hills 1975, Lidskii & Ozernoi 1979, Diener et al. 1997), the tidal radius, given by

\[ r_t \approx r_*(\frac{M_{BH}}{M_*})^{\frac{1}{3}}. \] (1)

The star is first heavily distorted, then disrupted. About half of the gaseous debris will be unbound and gets lost from the system (e.g., Young et al. 1977). The rest will be eventually accreted by the black hole (e.g., Cannizzo et al. 1990, Loeb & Ulmer 1997). The debris, first spread over a number of orbits, quickly circularize (e.g., Rees 1988, Cannizzo et al. 1990) due to the action of strong shocks when the most tightly bound debris interacts with other parts of the stream (e.g., Kim et al. 1999). Most orbital periods will then be within a few times the period of the most tightly bound matter (e.g., Evans & Kochanek 1989; see also Nolthenius & Katz 1982, Luminet & Marck 1985).

A star will only be disrupted if its tidal radius lies outside the Schwarzschild radius of the black hole, else it is swallowed as a whole (this happens for black hole masses larger than about $10^7 M_\odot$; in case of a Kerr black hole, tidal disruption may occur even for larger BH masses if the star approaches from a favorable direction (Beloborodov et al. 1992)). Larger BH masses may still strip the atmospheres of giant stars. Most theoretical work focussed on stars of solar mass and radius so far.

Explicit predictions of the emitted spectrum and luminosity during the disruption process and the start of the accretion phase are still rare (see Sect. 6.3 for details). The emission is likely peaked in the soft X-ray or UV portion of the spectrum, initially (e.g., Rees 1988, Kim et al. 1999, Cannizzo et al. 1990; see also Sembay & West 1993).

4. Tidal disruption events in active galaxies

Tidal disruption has occasionally been invoked to explain some exceptional events of variability in AGN or some general properties of AGN or LINERs.

The possibility of tidal disruption of a star by a SMBH was originally proposed as a means of fueling active galaxies (Hills 1975), but was later dismissed. Tidal disruption was invoked by Eracleous et al. (1995) in a duty cycle model to explain the UV brightness/darkness of LINERs.

1 Numerical simulations of the disruption process, the stream-stream collision, the accretion phase, the change in angular momentum of the black hole, the changes in the stellar distribution of the surroundings, and the disruption rates have been studied in the literature (e.g., Nduka 1971, Massa 1975, Nolthenius & Katz 1982, 1983, Carter & Luminet 1985, Luminet & Marck 1985, Evans & Kochanek 1989, Laguna et al. 1993, Diener et al. 1997; Lee et al. 1995, Kim et al. 1999; Hills et al. 1975, Gurzadyan & Ozernoi 1979, 1980, Cannizzo et al. 1990, Loeb & Ulmer 1997, Ulmer et al. 1998; Beloborodov et al. 1992; Frank & Rees 1976, Rauch & Ingalls 1998, Rauch 1999; Syer & Ulmer 1999, Magorrian & Tremaine 1999).
Table 2. Summary of the X-ray properties of NGC 5905, RX J1242–11 and RX J1614+75 during the giant flares. All three were characterized by very similar, extremely soft X-ray spectra during outburst with temperatures $kT_{bb} \approx 60 - 100$ eV, where $T_{bb}$ is the black body temperature derived from a black body fit to the data (cold absorption was fixed to the Galactic value in the direction of the individual galaxies). $L_x$ gives the intrinsic luminosity in the (0.1–2.4) keV band using $H_0 = 50$ km/s/Mpc (we note that this is a lower limit to the actual peak luminosity, since we most likely have not caught the source exactly at maximum light, since the spectrum may extend into the EUV, and since we have conservatively assumed no X-ray absorption intrinsic to the galaxies).

| name               | redshift | date of observation | $kT_{bb}$ [keV] | $L_{x, bb}$ [erg/s] | references                      |
|--------------------|----------|---------------------|-----------------|--------------------|---------------------------------|
| NGC 5905           | 0.011    | 11-16/7/1990        | 0.06±0.01       | $3 \times 10^{42}$ | Bade et al. 1996, Komossa & Bade 1999 |
| RX J1242–11        | 0.050    | 15–19/7/1992        | 0.06±0.01       | $9 \times 10^{43}$ | Komossa & Greiner 1999          |
| RX J1624+75        | 0.064    | 7-15/10/1990        | 0.097±0.004     |                    | Grupe et al. 1999              |

* Mean luminosity during the outburst; since the flux varied by a factor $\sim$3 during the observation, the peak luminosity is higher.

5. Tidal disruption flares from non-active galaxies

In the UV spectral region, two UV spikes were detected at and near the center of the elliptical galaxy NGC 4552. The central flare was interpreted by Renzini et al. (1995) as accretion event (the tidal stripping of a star’s atmosphere by a SMBH, or the accretion of a molecular cloud).

The discovery of a giant flare at soft X-ray energies from NGC 5905 was reported by Bade et al. (1996). The X-ray properties of the galaxy can be summarized as follows (see also Tab. 2, and Figs 1, 2): (i) The X-ray spectrum during outburst was ultra-soft ($kT_{bb} = 0.06$ keV). (ii) The total amplitude of variability amounts to a factor of $\sim 200$. (iii) The observed peak luminosity reached $L_x \approx 10^{42–43}$ erg/s. High quality optical spectra of this galaxy prior to the X-ray flare (Ho et al. 1995), and several years after the outburst (Schombert 1998, Komossa & Bade 1999) are of HII-type, with no signs of Seyfert activity. Komossa & Bade (1999) presented follow-up observations and discussed outburst scenarios. A summary of their results is given in the next section, plus an extended discussion of the possibility that the X-ray flare was due to a tidal disruption event.

A similar event was detected from the direction of the galaxy pair RX J1242–1119 (Komossa & Greiner 1999). In this case, the flare luminosity was even higher. It reached nearly $10^{44}$ erg/s in the ROSAT X-ray band (Tab. 2). Optical spectra taken of both galaxies reveal them to be non-active. No emission lines were detected.

6. Outburst scenarios

6.1. Alternatives to tidal disruption

Firstly, we note that based purely on a positional coincidence, an interlopper (flaring Galactic foreground object)
Fig. 1. Optical image of NGC 5905 from the digitized POSS, and positional error circle of the X-ray flare (taken from Bade et al. 1996).

Fig. 2. Long-term X-ray lightcurve of NGC 5905 (filled squares, and arrows for upper limits). The flare occurred during the ROSAT all-sky survey (RASS).

could not be excluded, given the limited spatial positional accuracy of ROSAT of at least several arcseconds.

However, known populations of galactic flaring sources show different temporal properties. In addition, the growing number of X-ray flares detected at the locations of bright, nearby galaxies (NGC 5905, RXJ1242-11, RXJ1614+75; a further candidate is presented by Reiprich & Greiner 2000), makes a chance coincidence increasingly unlikely.

Other sources of the X-ray emission related to sources within the galaxies NGC 5905 and RXJ1242–11 were reviewed by Komossa & Bade (1999) in some detail, including some order of magnitude estimates: Most outburst scenarios do not survive close scrutiny, because they cannot account for the huge maximum luminosity (e.g., X-ray binaries within the galaxies, or a supernova in dense medium), require extreme fine-tuning (e.g., a warm-absorbed hidden Seyfert nucleus), are inconsistent with the optical observations (gravitational lensing), or predict a different temporal behavior (X-ray afterglow of a Gamma-ray burst).

6.2. Tidal disruption model

Intense electromagnetic radiation will be emitted in three phases of the disruption and accretion process: First, during the stream-stream collision when different parts of the bound stellar debris first interact with themselves (Rees 1988). Kim et al. (1999) have carried out numerical simulations of this process and find that the initial luminosity burst due to the collision may reach $10^{41}$ erg/s, under the assumption of a BH mass of $10^6 M_\odot$ and a star of solar mass and radius. Secondly, radiation is emitted during the accretion of the stellar gaseous debris. Finally, the unbound stellar debris leaving the system may shock the surrounding interstellar matter like in a supernova remnant and cause intense emission.
The luminosity emitted if the black hole is accreting at its Eddington luminosity can be estimated by $L_{\text{edd}} \approx 1.3 \times 10^{38} M/M_\odot\text{ erg/s}$. In case of NGC 5905, a BH mass of at least $\sim 10^5 M_\odot$ would be required to produce the observed $L_x$, and a higher mass if $L_x$ was not observed at its peak value. For comparison, BH masses of $M_{\text{BH}} \lesssim 10^6-7 M_\odot$ have recently been reported by Salucci et al. (1999) for the centers of some late-type spiral galaxies. Alternatively, the atmosphere of a giant star could have been stripped instead of a complete disruption event. It is interesting to note that NGC 5905 possesses a complex bar structure (Friedli et al. 1996) which might aid in the fueling process by disturbing the stellar velocity fields.

Using the black body fit to the X-ray spectra of NGC 5905 and RXJ1242–11, we find the fiducial black body radius to be located between the last stable orbit of a Schwarzschild black hole, and inside the tidal radius.

We note that many details of the tidal disruption and the related processes are still unclear. In particular, the flares cannot be standardised. Observations would depend on many parameters, like the type of disrupted star, the impact parameter, the spin of the black hole, effects of relativistic precession, and the radiative transfer is complicated by effects of viscosity and shocks (Rees 1990). Uncertainties also include the amount of the stellar debris that is accreted (part may be ejected as a thick wind, or swallowed immediately). Related to this is the duration of the flare-like activity, which may be months or years to tens of years (e.g., Rees 1988, Cannizzo et al. 1990, Gurzadyan & Ozernoi 1979).

7. Search for further X-ray flares

We performed a search for further cases of strong X-ray variability (Komossa & Bade 1999) using the sample of nearby galaxies of Ho et al. (1995) and ROSAT all-sky survey and archived pointed observations. The sample of Ho et al. has the advantage of the availability of high-quality optical spectra, which are necessary when searching for ‘truly’ non-active galaxies. 136 out of the 486 galaxies in the catalogue were detected in pointed observations. For ‘truly’ non-active galaxies, $\sim 10^4$ M/M$_\odot$ would be required to produce a BH mass of $M_{\text{BH}} \lesssim 10^6-7 M_\odot$ have recently been reported by Salucci et al. (1999) for the centers of some late-type spiral galaxies. Alternatively, the atmosphere of a giant star could have been stripped instead of a complete disruption event. It is interesting to note that NGC 5905 possesses a complex bar structure (Friedli et al. 1996) which might aid in the fueling process by disturbing the stellar velocity fields.

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8. Future perspectives

Such X-ray outbursts provide important information on the presence of SMBHs in non-active galaxies, the accretion history of the universe, and the link between active and normal galaxies. Future X-ray surveys (like the one that was planned with ABRIXAS, or the one that will be carried out with MAXI) will be valuable in finding further of these outstanding sources.

In particular, rapid follow-up optical observations will be important in order to detect potential emission lines that were excited by the outburst emission. In case of a giant tidal disruption flare in an active galaxy, this would also provide an excellent chance to map the properties of the broad line region.

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Preprints of this and related papers can be retrieved from our webpage at http://www.xray.mpe.mpg.de/~skomossa/.

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