Similarity of the variability patterns in the Exosat and Ginga folded light curves of the Seyfert galaxy NGC 6814

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ABSTRACT

The Seyfert galaxy NGC 6814 is known to show periodic variation of its X-ray luminosity. We found that the sequences of peaks (variability patterns) in the folded X-ray light curves constructed from the Exosat and Ginga data are remarkably similar when one ignores amplitudes of the peaks and considers only their phases. The stable pattern consists of five peaks which are present in the both curves. The phases of the corresponding peaks coincide with an accuracy of about 10 degrees. The probability that this coincidence occurs by chance is less than about 1% according to the most conservative estimate. The observed stable pattern of peaks may be produced by a stable distribution of “bright spots” on the accretion disk surface, e.g. by strong vortices or magnetic flux tubes.

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1. Introduction

The Seyfert galaxy NGC 6814 shows a very stable periodic behaviour in the form of repeated X-ray flares with a period $P_0 = 12200$ sec in both the Exosat data (Mittaz & Branduardi-Raymont 1989; Fiore et al. 1992a, b) and the Ginga data (Done et al. 1992a, b). The stability of the period estimated by Fiore et al. is $P_0 \lesssim 5 \times 10^{-6}$. Theoretical models which had been suggested by several authors to explain the observed periodic flaring have been critically discussed by Abramowicz (1992), and the main points of his discussion were summarized in a recent review article by Wallinder et al. (1992).

In this paper we describe a strong observational constraint for possible theoretical models which we have found by comparing the folded light curves constructed from the Exosat and Ginga data. Figures 1 and 2 show the NGC 6814 light curves obtained by Exosat (Fiore et al. 1992b) and Ginga (Done et al. 1992b), both folded on the period $P_0 = 12200$ sec. The Exosat folded light curve clearly shows one major flare and less clearly several smaller flares, while the Ginga light curve shows three major flares and several smaller ones. Although the first impression may be that these curves are very different, a closer look reveals a striking similarity between them: if one ignores amplitudes of the flares and considers only their phases, one finds that the phases of the corresponding five Exosat and Ginga flares differs by less than 10 degrees. Probability that this coincidence may occur by a pure chance is very small and thus it is quite possible that we do observe a pattern of five flares which have not changed their phases during the six years between the Exosat and Ginga observations.

2. Fitting the variability patterns to the bright spots model

Abramowicz et al. (1991, 1992a, b, c) have proposed that the observed periodic variability of NGC 6814 is due to the orbital motion of a pattern of a few bright spots located somewhere on the central part of an accretion disk. Modulation of the observed intensity is due to the relativistic Doppler effect, gravitational lensing and occultations by the outer parts of the disk. The gravitational lensing occurs when one of the bright spots moves, with respect to the observer, almost exactly behind the central black hole and this situation only happens for accretion disks with a nearly edge-on orientation.

For an assumed spot pattern (phase $\varphi_j$, size $\Delta \varphi_j$, intensity $I_j$ of each individual spot, i.e. for $j = 1, ..., N$ where $N$ is the number of spots) and for an assumed set of orbital parameters (mass of the central black hole $M$, orbital radius $r$, inclination of the axis of the accretion disk with respect to the line of sight $\theta$) one computes the exact shape of the model light curve. By fitting it to the observed light curve, one deduces the values of the parameters describing the spot pattern and the orbit. Technical details of this procedure (which includes all general relativistic effects with no approximations) have been described by Abramowicz et al. (1992b), Zhang and Bao (1991), Bao (1992), Karas and Bao (1992), and Bao and Stuchlík (1992).

The existence of bright spots is not postulated ad hoc to explain the variability of NGC 6814, but it was suggested a few years earlier by Abramowicz et al. (1989) in
connection with a more typical, noise-like, X-ray variability found for most AGN. Typically, the X-ray variability of AGN in the range of time scales between $10^3$ sec and $10^5$ sec is featureless and shows no preferred frequency, $f$. Its power can be approximated by $1/f^\beta$ noise, with $1 \leq \beta \leq 2$. Abramowicz et al. (1989, 1991) demonstrated that this can be explained by orbital motion of several hundred of small spots at a range of radii on the accretion disk surface. The idea of bright spots on accretion disks in active nuclei is now gaining strong observational support (see e.g. Veilleux & Zheng 1991; Zheng et al. 1991; Miller et al. 1992; Witta et al., 1991, 1992; Dultzin-Hacyan et al. 1992). In this context NGC 6814 is unique because in addition to several hundreds small spots which produce the observed (and typical) $1/f$ noise, it also has a few very strong spots which produce the observed periodic signal (unique to this source).

According to the bright spots model, the brightness of each individual spot may change from period to period, but the positions (orbital phases) of the strong spots should remain fairly constant, although not exactly fixed, as they should reflect the $P_0 \lesssim 5 \times 10^{-6}$ period stability. Thus, there should be the same variability pattern defined by the strong spots in the Exosat and Ginga light curves — repeated major flares should occur at almost the same orbital phases independently of their varying amplitudes. As a consequence, phase differences between the major flares should be almost constant in time, i.e. they should be constant with a similar accuracy as the period is constant in time.

\textit{i) The fits to Exosat and Ginga folded light curves.}

We have fitted to both Exosat and Ginga data several theoretical light curves calculated from the bright spots model. The quality of the fit was judged by the $\chi^2$ test calculated according to the formula,

$$
\chi^2 = \frac{1}{k-n} \sum_{i=1}^{k} \left( \frac{I_O(\varphi_i) - I_M(\varphi_i)}{\sigma_O(\varphi_i)} \right)^2.
$$

(2.1)

Here $\varphi_i$, $I_O(\varphi_i)$, $\sigma_O(\varphi_i)$ are the phases, intensities (measured in counts per second), and errors of the observed $k$ data points, $I_M(\varphi_i)$ are the intensities calculated from the model, and $n = 3 \times N + 4$, where $N$ is the number of the spots in the model, is the number of the free parameters.

First we found that if the orbital parameters are the same for both Exosat and Ginga, then the best fit model gives,

$$
M = 9 \times 10^6 M_\odot, \quad r = 6r_G, \quad \theta = 85^\circ.
$$

(2.2)

We then made fits with the orbital parameters (2.2) fixed, but with several different numbers of spots and several different spot patterns. The best fits (minima of $\chi^2$ with respect to $\varphi_j, \Delta \varphi_j, I_j$ with $n = 3 \times N + 1$ and the orbital parameters fixed) for several different numbers of spots are shown in Figure 1 for the Exosat fits and in Figure 2 for the Ginga fits. Figure 3 shows how the $\chi^2$ calculated from equation (2.1) depends on the postulated number of spots. One concludes from these Figures that the fits of the models
with 3 or more spots are very good. For Exosat data the best fit is given by the model with 4 spots, for Ginga the minimum of $\chi^2$ is very shallow and one can only say that the best fit is given by models with 5, 6, or 7 spots.

Figure 4 and Table 1 show the locations, sizes and intensities of the spots from the best fit models to the Exosat and Ginga data. The basic argument of our paper is that the five major spots have very similar phases. The maximal phase difference between the corresponding Exosat and Ginga spots is $\Delta \varphi = 0.029$ (i.e. 10 degrees). We argue that this coincidence could not possibly occur by pure chance. The simplest estimate of the probability that for two sets of $N$ ordered numbers between 0 and 1 the differences between corresponding numbers are less than $\Delta \varphi$ is $p_N(\Delta \varphi) \approx (\Delta \varphi)^N$. This gives $p_5(0.029) = 2 \times 10^{-8}$ and, if only the three major spots are considered, $p_3(0.029) = 3 \times 10^{-5}$. Thus, one may conclude that the coincidence between the three major spots in the Exosat and Ginga light curves cannot occur by chance.

**ii) The probability of coincidence of two N-spot patterns.**

One can argue that the locations of the peaks of the flares in the Exosat and the Ginga light curves are not truly random, because if two flares are located too close to each other, they would be mistaken for one spot. This means that when the probability is calculated, the Exosat and Ginga distributions of spots should be compared only with those distributions in which all the spots in one set are distant from each other by more than a given minimal separation $\delta \varphi$. By increasing the minimal separation one increases the probability of the coincidence of the two sets of numbers. Thus, if in a real situation there are several flares separated by $\delta \varphi_0$ or more, one overestimates the probability by assuming $\delta \varphi = \delta \varphi_0$, because these flares could be still recognized as separate with a smaller separation constant. Figure 4 shows that all the spots in one set (either Exosat or Ginga) are separated by more than 0.1 in phase. Therefore, the data is consistent with $\delta \varphi \lessapprox 0.1$ (about 30 degrees).

We have calculated by Monte Carlo simulations what is the probability $p_N(\delta \varphi, \Delta \varphi)$ that for two sets of $N$ spots separated by at least $\delta \varphi$, the phase differences between the corresponding spots are less than $\Delta \varphi$, assuming in addition that the phases in the second set may all be adjusted by a constant phase shift in order to make $\Delta \varphi$ as small as possible. Results of these calculations are presented in Figure 5.

From the fits discussed in this Section and presented in Figures 1, 2, 3, 4 and in Table 1 we obtained $3 \leq N \leq 5$, $\delta \varphi \leq 30$ degrees, and $\Delta \varphi \leq 10$ degrees. As can be seen from Figure 5, this corresponds to an upper limit to the probability that such a coincidence could occur by chance, $p_5 < 0.01$ (and $p_3 < 0.04$). Because the probability is small, we conclude that the coincidence between the phases of the peaks in the Exosat and Ginga light curves is real and reflects an important intrinsic property of the source.

The stability of the variability pattern found by us on the basis of the Exosat and Ginga data and attributed to five spots present on a fixed orbit, confirms an earlier suggestion by Fiore et al. (1992a), made on the basis of four Exosat observations, that the strong fourth harmonic in the Fourier power spectrum of the variability of NGC 6814 may
be an intrinsic property of this source. The fourth harmonic has its frequency equal to five times that of the fundamental one.

Figure 6 shows the vectors corresponding to shifts from the *Exosat* to *Ginga* positions of the spots. The Figure seems to suggest that the spot pattern undergoes systematic rather than chaotic changes. It would be very important to see whether this behaviour is confirmed by the *Rosat* data because this may be crucial in deciding the physical nature of the spots.

### 3. Discussion

Although the physical nature of the spots is mostly irrelevant for the arguments presented here, we would like to point out that Abramowicz *et al.* (1992a) discussed observational evidence in favour of the possibility that the small bright spots could be small, transient vortices. The strong spots responsible for the periodic signal in NGC 6814 could be giant and long-lived vortices, similar to the Jupiter’s Great Red Spot. The Great Red Spot is a very long lived vortex: it has survived more than $3 \times 10^5$ rotational periods of Jupiter since it was discovered by Galileo. It is known that the Great Red Spot slowly moves along its orbit (has a longitude motion). Numerical hydrodynamical simulations (see Abramowicz *et al.* 1992a for references) show that typically in a situation where many interacting vortices are present, very strong vortices are rare and have long lifetimes, while small vortices are frequent and relatively short lived.

Other possible explanations for stable and strong bright spots on the accretion disk surface include a stable complex of magnetic spots such as in rapidly rotating solar type stars, a perturbation due to an additional center of accretion, *e.g.* a small star or black hole orbiting inside the accretion disk, non-axially symmetric instabilities, spiral structures, etc.

The value of the mass obtained from the fit, $M = 9 \times 10^6 M_\odot$, agrees very well with that estimated by Padovani & Rafanelli (1988) who got $M = 6.68 \times 10^6 M_\odot$ from a kinematic analysis of the the broad emission lines. The same authors estimated the bolometric luminosity of NGC 6814 to be about $10^{44}$ erg sec$^{-1}$, and therefore the bolometric to Eddington luminosity ratio to be $\lambda \approx 10^{-1}$.

The high inclination obtained in our fit, $\theta = 85^\circ$, needs a few words of comment. Recently Yamauchi *et al.* (1992) analysed the *Ginga* data on the strong X-ray reflection component consisting of an iron line and broad hump of emission extending from about 10 keV to 100 keV, of which only the lower end is yet detected. (See also Nandra *et al.* 1992 and Matsuoka, 1992.) Yamauchi *et al.* calculated the width of the iron line profile (FWHM) for different inclinations and concluded that the inclination of the disk must be rather low, $\theta \approx 8^\circ$, because for higher inclinations the Doppler effect would broaden the profile more than the observational upper limit (0.4 ± 0.4) keV obtained by Kunieda *et al.* (1990). However, in our opinion this result strongly depends on the assumed geometry. According to our calculations, when one includes the effect of occultation of the innermost part of the disk by its outer parts (this is important at high inclination, but was ignored by Yamauchi *et al.*), the observational limit for the FWHM is met, and the shape of the
light curve is only very little changed. The presence of absorption features in NGC 6814 was noticed by several authors, e.g. by Done et al. (1992b), and this independently points to a possible importance of occultations.

One should stress that arguments based on the iron line cannot be at the present time considered as very reliable because some of the most fundamental aspects of the data on the iron line in NGC 6814 are not understood at all. In particular, the equivalent width of the line, $EV = 300 - 500$ eV, is 2 to 3 times larger than expected from the standard theory. It is worth quoting here a popular explanation for this which also assumes a high inclination in agreement with what we have found: “One possible solution is that they [NGC 6814 and NGC 5548] are observed at high inclination so that what would otherwise be secondary effects now dominate.” (Fabian 1992).

4. Conclusions

We found that the variability patterns present in the Exosat and Ginga folded light curves are remarkably similar — the corresponding peaks differ in phase by less than 10 degrees. Predictions from the bright spots model agree very well, in a strict quantitative way, with the stability of the variability pattern. According to our interpretation of the data, not only does one clearly and directly see relativistic rotation of the disk in the Exosat and Ginga folded light curves, but there is also a serious possibility that these curves display, again quantitatively, the influence of the slow inward accretion flow which proceeds on the viscous timescale.

Our model is directly testable: it should be definitively rejected if some future observations in a similar range of X-ray spectrum show no periodic variability or a different variability pattern. However, if the stability of the variability pattern suggested in our paper is confirmed by a third independent observation (e.g. in UV or optical, or in X-rays by Rosat), then the probability that in all three cases the coincidence occurs by pure chance would be negligibly small. Then, not only our model will be proved correct, but in addition the long awaited unquestionable proof of the correctness of the AGN paradigm will be finally at hand.

The quality of the fits of the model light curves to those observed is excellent, as we have demonstrated in terms of the $\chi^2$ test. Thus, we conclude that a detailed quantitative analysis of the data strongly supports the bright spots model. Whether the other models (Syer, et al., 1991, Rees, 1992, Sikora and Begelman, 1992, Done and King, 1992) could also explain the variability pattern stability in the same accurate and quantitative way remains to be seen.

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Figure and Table captions

Figure 1: The best fits to the Exosat folded light curve for the bright spot model with $N = 1, 3, 4, 5$ spots. The theoretical curves are shown by the broken lines. The Exosat data was collected during the “long look” 1985/289 with the duration of about two days and corresponds to photon energies from 2 keV to 6 keV.

Figure 2: The best fits to the Ginga folded light curve for the bright spot model with $N = 4, 5, 6, 7$ spots. The theoretical curves are shown by the broken lines. The Ginga light curve corresponds to the total duration of about three days and photon energies from 2.24 keV to 5.69 keV.

Figure 3: The $\chi^2$ values for the best fits to both Exosat and Ginga folded light curves with different number of spots.

Figure 4: The spot patterns used in our model for Exosat and Ginga fits.

Figure 5: Probability $p_N(\delta \varphi, \Delta \varphi)$ that two sets of $N$ observed phases (ordered numbers between 0 and 1 separated in each set by at least $\delta \varphi$) coincide with accuracy at least $\Delta \varphi$. Both $\delta \varphi$ and $\Delta \varphi$ are given in degrees.

Figure 6: Shifts in the spots locations from Exosat to six years later Ginga positions. A constant phase shift of $10^\circ$ was added to all Ginga phases to make our argument more apparent. The Figure clearly shows that the pattern undergoes a systematic change: there is almost exactly linear relation between the phase shift and the phase. In our model such a relation is expected as a direct consequence of the very slow inward accretion flow in addition to the circular motion. The spots are not moving on circles, but rather on very tight spirals, which correspond to spiral flow lines in the accretion disk. Thus, the spots are located at slightly different radii and therefore they have slightly different periods. These differences are too small to affect the measured period stability, but sufficient to produce, in six years, the very small shifts seen in Figure 6. Quantitatively, because the shift for the spot No. 2 is by $20^\circ$ greater than for the spot No. 4, one calculates directly from the observational data that the spot No. 2 moves $\Delta r \approx 10^{-6} r_0$ closer to the centre than the spot No. 4. This number should be approximately of the same order as the ratio of the orbital to viscous time scale, estimated from the standard accretion disk theory, $t_{vis}/t_{orb} \approx \lambda^2 \alpha$. Thus, the Shakura-Sunyaev $\alpha$ viscosity parameter should be of the order of $10^{-4}$, which is rather low, but quite reasonable.

Table 1: The three major spots are indicated by asterisk *. Intrinsic intensities and energies of spots are given in arbitrary units.
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| Spot’s number | Spot’s phase number | Spot’s phase Ginga (°) | Spot’s phase Exosat (°) | Spot’s width Ginga | Spot’s width Exosat | Spot’s intensity Ginga | Spot’s intensity Exosat | Spot’s energy Ginga | Spot’s energy Exosat | Phase difference Ginga–Exosat (°) |
|---------------|---------------------|------------------------|-------------------------|------------------|-------------------|----------------------|----------------------|------------------|------------------|------------------------------|
| *1            | 1                   | 0.10 (37°)             | 0.08 (29°)              | 0.064            | 0.064             | 1.00                  | 0.35                 | 1.00             | 0.35             | 0.022 (8°)                  |
| 2             | 2                   | 0.25 (90°)             | 0.21 (77°)              | 0.024            | 0.008             | 0.50                  | 0.36                 | 0.20             | 0.05             | 0.032 (11°)                 |
| 3             | 3                   | 0.33 (119°)            |                         | 0.021            | 0.008             | 0.30                  | 0.30                 | 0.10             |                  |                              |
| *4            | 4                   | 0.48 (172°)            | 0.51 (182°)             | 0.068            | 0.057             | 0.77                  | 1.50                 | 0.73             | 1.33             | -0.029 (−10°)               |
| *5            | 5                   | 0.82 (296°)            | 0.84 (301°)             | 0.032            | 0.032             | 1.20                  | 0.30                 | 0.60             | 0.15             | -0.016 (−6°)                |
| 6             | 6                   | 0.96 (344°)            | 0.94 (337°)             | 0.016            | 0.008             | 0.36                  | 0.16                 | 0.10             | 0.10             | 0.019 (7°)                  |