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Patterns and coincidences in the light curves of active galaxies

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ABSTRACT

We draw attention to some intriguing coincident patterns in the optical light curves of NGC 4151 and 5548. Inspecting the light curves of these two classic Seyferts, we find evidence for at least five occurrences of a similar sequence of variations. This pattern consists of a $\sim$2-yr-long sequence of shorter flares, with a total energy of (3–5) $\times 10^{50}$ erg in the *B* band. We predict that the ongoing monitoring campaign on NGC 5548 should soon reveal more occurrences of this general pattern if it is truly recurrent. We speculate on the possibility that this pattern is associated with a fundamental/universal 'unit' of variability in active galaxies, and discuss a possible connection with the variability properties of QSOs.

Key words: galaxies: active – galaxies: individual: NGC 4151 – galaxies: individual: NGC 5548 – galaxies: Seyfert.

1 INTRODUCTION

Optical–UV variability was long ago established as a fundamental property of active galactic nuclei (AGN) and has puzzled us ever since. In recent times astronomers have focused their interest not so much on the physical origin of the continuum variations, but into using them to infer the geometry and dynamics of the emitting gas of the broad-line region through reverberation mapping techniques (e.g. Peterson 1993, and references therein). Although emission-line variability studies have witnessed a substantial progress in the past few years, the nature of the continuum variations themselves is still not well understood.

AGN vary in a rather chaotic way, with no indications of periodicities, but some regularities have been reported. In the 1970s, Lyutyi and co-workers suggested that AGN variability could be described in terms of two basic components: (1) a *rapid component* – a sharp peak with a time-scale of weeks, and (2) a *slow component* – a broad bump a few years long, on top of which the rapid component sits (Lyutyi 1972, 1977, 1979; Dibaĭ & Lyutyi 1984; Lyutyi & Oknyanskii 1987). This overall pattern was further confirmed by Pica & Smith (1983), Gill et al. (1984), Alloin et al. (1986) and Smith et al. (1993). Alloin and co-workers, in particular, found that NGC 1566 exhibits recurrent outbursts interspaced by quiescent periods. The global time-scale of the outbursts is $\sim$3.5 yr, but the brightest stages last only a few weeks.

One of the major goals of variability studies is, of course, to identify and characterize the physical processes responsible for the variations. Establishing whether recurrent patterns or well-defined sequences of events occur in the light curves of AGN would be an important step towards this goal. This paper re-opens the discussion of variability patterns by examining some intriguing coincidences in the optical light curves of the two best monitored type 1 Seyferts: NGC 4151 and 5548. Section 2 introduces the data sets used in this work. In Section 3 we identify several occurrences of the same pattern of variations in these two light curves. The significance of these coincidences is assessed in Section 4 by means of cross-correlation techniques. A discussion of our results, their potential implications for AGN models and a possible extrapolation to high-luminosity QSOs is presented in Section 5. Finally, Section 6 summarizes our findings.

2 THE OPTICAL LIGHT CURVES OF NGC 4151 AND 5548

The data used in this study are the *B*-band light curves of NGC 4151 and 5548. The data for NGC 4151 consist of 834 observations in the 1968–1990 period, compiled and intercalibrated by M. Penston and T. Snijders, who also subtracted the contribution from the host galaxy (Snijders 1991 – see also Gill et al. 1984 and Lyutyi & Oknyanskii 1987). The apparent magnitudes were converted to *B*-band lumin-

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osity (L_B) applying an $E(B-V)=0.16$ reddening correction (Rieke & Lebofsky 1981) and assuming a distance of 27 Mpc. This distance includes a correction to allow for the infall of NGC 4151 towards Virgo (Aretxaga & Terlevich 1994).

NGC 5548 has been intensely monitored by the AGN Watch consortium since 1989 (Korista et al. 1995, and references therein). The data used here consist of monochromatic fluxes at 5100 Å for 559 points covering the 4.8-yr interval between 1988.9 and 1993.7. The estimated host galaxy flux in the 7.5 × 5 arcsec^2 slit used in the observations is 3.4×10^{-15} erg s^{-1} cm^{-2} Å^{-1} at 5100 Å (Korista et al. 1995; Peterson et al. 1995; Romanishin et al. 1995). Once this component was subtracted, the nuclear fluxes at 5100 Å were converted to the B band (3900–4900 Å) assuming a spectral index $\alpha=-1.23$ ($F_\nu \propto \nu^\alpha$; Edelson & Malkan 1986). L_B was then computed applying an $E(B-V)=0.1$ reddening correction (Tsvetanov & Yancoulova 1989) and assuming a distance of 103 Mpc, corresponding to $z=0.0173$ (de Vaucouleurs et al. 1991) and $H_0=50$ km s^{-1} Mpc^{-1}.

The two light curves are plotted in Fig. 1. The peak-to-peak variations in the light curves of these two type 1 Seyferts are $3\times10^9\,L_\odot$ for NGC 4151 and $4\times10^9\,L_\odot$ for NGC 5548. The minimum recorded luminosities for these two objects are also similar: $10^9\,L_\odot$ for NGC 4151 (which occurred in 1984.4) and $9\times10^8\,L_\odot$ for NGC 5548 (in 1992.5). Taking into account the uncertainties in the reddening correction, starlight subtraction and distances, these values can be regarded as consistent with each other. In any case, the identification of patterns in the variations is not critically affected by the uncertainties in the absolute luminosity scales.

3 IDENTIFICATION OF PATTERNS

The identification of patterns in the data is complicated by the numerous gaps in the observations and the less than ideal error bars. However, a close examination of Fig. 1 reveals some surprising coincidences.

3.1 Pulse 92 in NGC 5548 and Pulse 70 in NGC 4151

The first similarity which strikes the eye when comparing the two light curves in Fig. 1 is that between the 'pulse' starting in 1992.3 and going till the end of the data train at 1993.7 in NGC 5548 (hereafter referred to as 'pulse 92') and the variations of NGC 4151 between 1970.1 and 1972.6 ('pulse 70'). The two sequences are overlayed in Fig. 2. Pulses 70, 92 and three other similar events discussed below are plotted in Fig. 3.

Both pulses 70 and 92 start with an initial rapid, ~0.3-yr-long flare. These flares are labelled 70_1 and 92_1 in Fig. 3(b), where in order to better illustrate the main features in the light curves we have smoothed the pulses by a Gaussian filter with a standard deviation of 1 d (the original data are shown in Fig. 3a). This rapid flare seems to play the role of a 'starting gun' to the big and long-lasting flare (70_2–70_4 and 92_2–92_3) which follows it. In NGC 4151 the second and most luminous peak (70_2) occurs 0.75 yr after the peak of the starting shot, while the corresponding delay in NGC 5548 is 0.6 yr (92_2). The amplitudes and timing of the starting shots are somewhat different in the two objects, but from then on

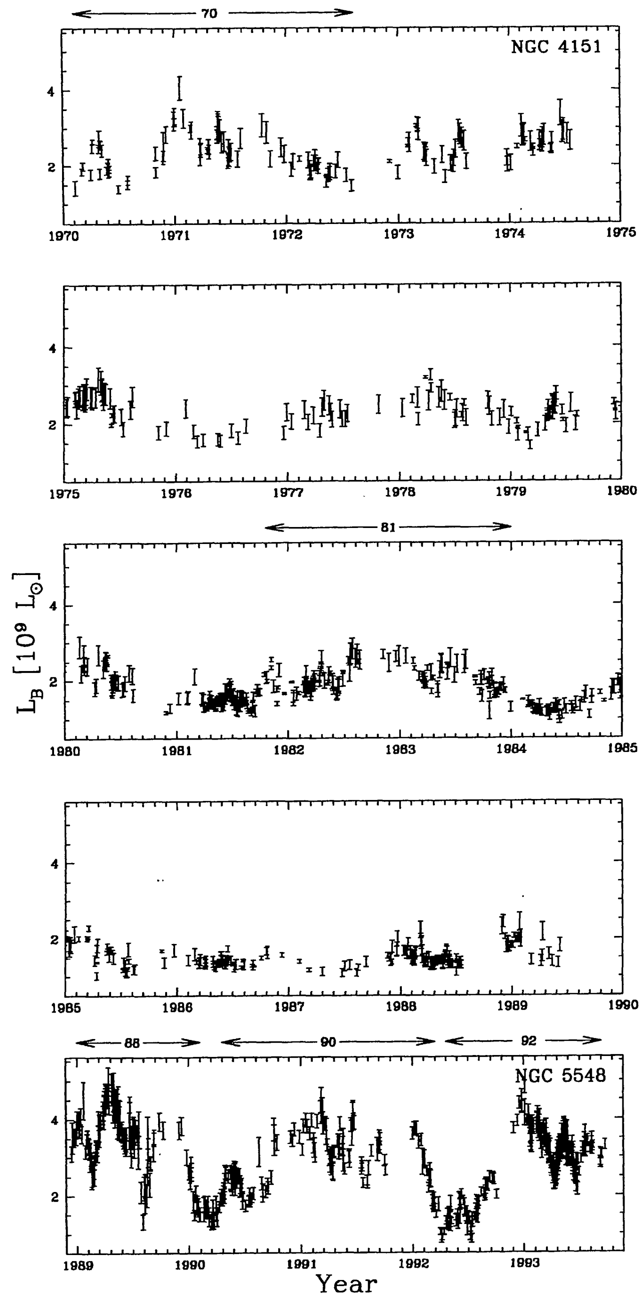

Figure 1. *B*-band light curves of NGC 4151 and 5548. Pulses 70, 81, 88, 90 and 92 (discussed in the text) are indicated.

their light curves are remarkably similar. After the maximum luminosity both objects undergo a rapid decay, which is reversed ~0.25 yr after the maximum, leading to a new peak (70_3 and 92_3) ~0.1 yr later. The overall pattern of the 'slow component' could be described as that of a 'damped oscillator': a decaying pulse with a time-scale of ~1–2 yr with ~0.3-yr oscillations on top of it.

Pulses 70 and 92 may be somewhat different quantitatively (note the different scales for the two pulses in Fig. 2), but are similar qualitatively. This similarity strongly suggests a common underlying physical process causing the variations. The most direct way of assessing the reality of this

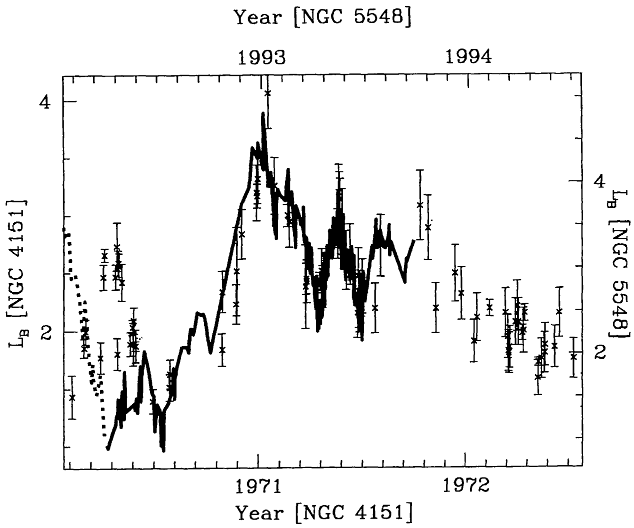

Figure 2. Superposition of the light curves of NGC 4151 from 1970 to 1973 (error bars) to that of NGC 5548 22 yr later (thick dotted and solid lines). Bottom and left axes correspond to NGC 4151, while top and right axes correspond to NGC 5548. Luminosities in units of $10^9 L_\odot$.

coincidence is to look for other occurrences of this general pattern. At least three other such coincidences can be found in the data. These are discussed next.

3.2 Pulses 88, 90 and 92 in NGC 5548

We now compare pulse 92 in NGC 5548 with pulse 90, defined as the interval between 1990.2 and 1992.2 also in NGC 5548. Pulses 92 and 90 have similar starting shots (92_1 and 90_1) and initial rise after that. The second peak (92_2), however, either was not as strong in 90 as in 92 or it was simply missed by the sparse sampling in this region of pulse 90. The local minimum at 1991.3 in 90, however, is well matched by that later observed in 1993.3 in pulse 92. Overall, the amplitude and time-scale of the two pulses match each other reasonably well. Note that pulse 92 is incomplete, so the late behaviour of the pulses cannot be compared. Unless a new pulse occurred late in 1993, we expect the NGC 5548 light curve to present a broad hump like that observed between 1991.6 and 1992.2 in pulse 90 (90_4). This prediction can be readily tested when the AGN Watch group publishes the data for the period after 1993.7. In fact, as nearly four years have gone by since the last observation

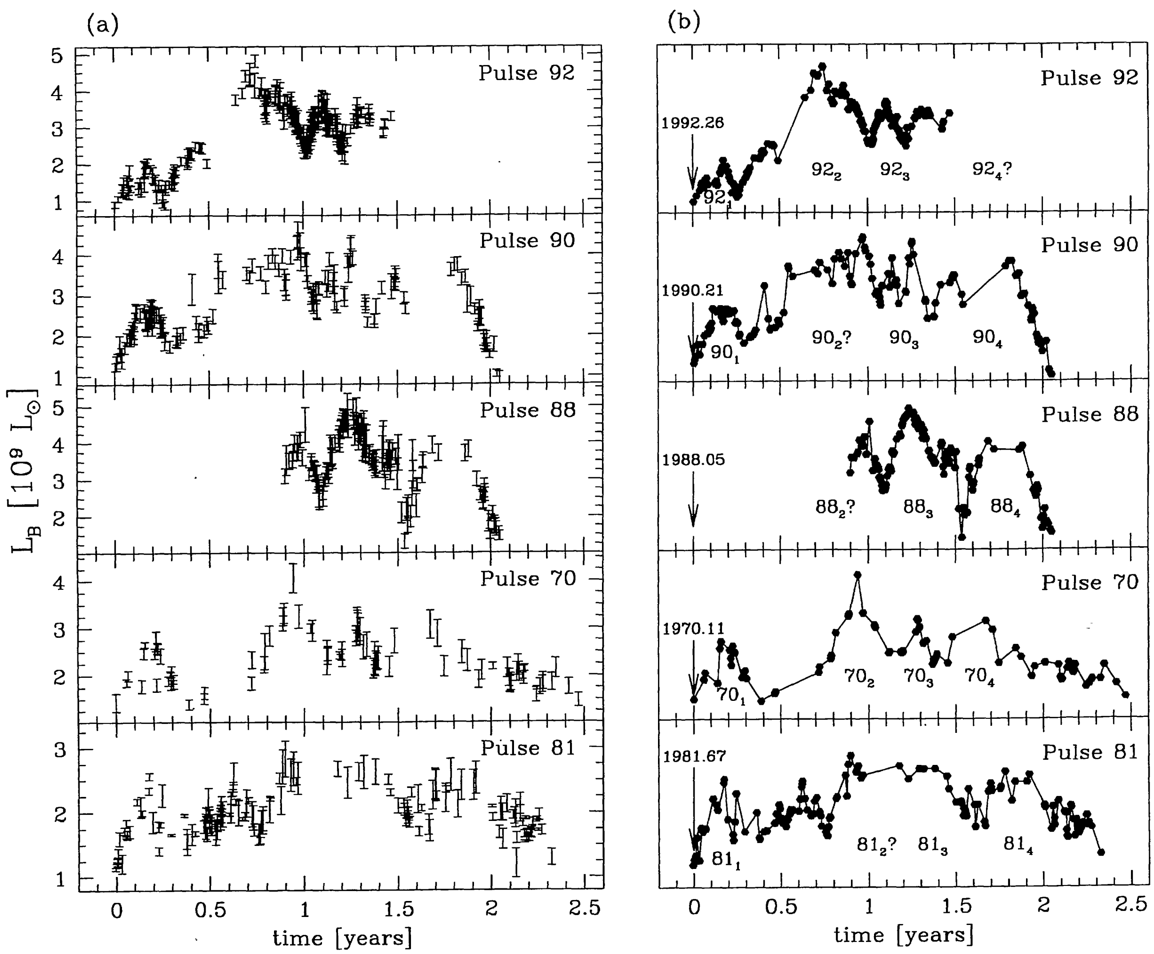

Figure 3. (a) Blow-up of pulses 70, 81, 88, 90 and 92. (b) Same as in panel (a), but after smoothing the pulses with a Gaussian filter with a standard deviation of 1 d. The starting dates are indicated. Dots correspond to observed dates.

of NGC 5548 used in this paper, the new data will be extremely important for testing whether patterns such as pulses 90 and 92 are really recurrent.

The variations in the period from 1989 to 1990 in NGC 5548 ('pulse 88') also seem to fit on a pattern similar to that of pulses 90 and 92. This is best seen by shifting pulse 90 back by 2 yr, so that it starts around 1988.1 (see Fig. 3). Although the initial phases of the pulse evolution cannot be compared, given that the observations started in the 'middle' of the pulse, there is a good correspondence between the peaks at 1991.2 and 1989.0, and between the peaks labelled 90_4 and 88_4 in Fig. 3(b). The only substantial difference between these two pulses is that while pulse 88 has a single 0.2-yr-long peak when the pulse is ~ 1.1 yr old (at 1989.3), the corresponding phase in pulse 90 shows two smaller peaks (see Fig. 3). Overall, however, the matching is good in both amplitude and time-scale.

3.3 Pulses 70 and 81 in NGC 4151

Going back to the NGC 4151 light curve, an event similar to pulse 70 was observed in the period from 1981.7 to 1984.0 ('pulse 81'). The starting shots (70_1 and 81_1) have similar amplitudes and durations. Comparing the two pulses we see that the global maximum (at 1971.05 in pulse 70) was probably missed in pulse 81 – it should have occurred around 1982.6, where there is a gap in the data. The hump at 1983.0 (81_3) does match that of 70 at 1971.4 (70_3), as does the later decay in luminosity. The agreement here is not as impressive as that between 70 and 92 or between 92, 90 and 88, but the global behaviour of the two pulses is undoubtedly similar.

3.4 Other possible coincidences in NGC 4151

A few other possible matches can be found in the light curve of NGC 4151 by sliding pulse 70 (or pulse 81) over the light curve so that it starts at any of the following dates: 1972.3, 1973.5, 1976.9 and 1978.6 (see also Section 4 below). None of these matches is as convincing as the previous ones, but it must be stressed that this sort of analysis is severely affected by the poor sampling throughout most of the light curve of NGC 4151. Also, pulses may occasionally overlap in time, which would complicate their identification. Such a superposition of pulses does indeed seem to have occurred in NGC 4151 between ~ 1973.5 and 1974.5. If we associate the small ~ 0.3-yr-long flare centred on 1972.5 with a starting shot like 70_1, then the 1973.2 and 1973.55 peaks are very well matched by 70_2 and 70_3 respectively. From 1974 onwards, however, the light curve reverses its downward trend and goes into a new luminous phase which lasts until the end of 1975. This indicates that a new pulse occurred sometime around 1973.5, probably overlapping with the 70_3-like peak of the previous event. The starting shot of this new event would have peaked around 1973.7, where there is a gap in the data. The second and third maxima, corresponding to 70_2 and 70_3, would be placed at ~ 1974.5, where a local maximum is indeed found, and 1974.8, where again the data are missing. The decay from 1975 onwards is also well matched (both in shape and amplitude) by the late decay of pulse 70, which gives some support to this interpretation.

3.5 Pulse energies

A further way to compare the pulses identified above is to compute their energies. Integrating the segments of the light curves corresponding to pulses 70, 81, 88, 90 and 92, we find that they contain B-band energies of 0.60, 0.61, 0.48, 0.73 and 0.49×10^{51} erg respectively. While these values are similar to each other, we note that pulses 88 and 92 are incomplete, so their energies are certainly underestimated.

A direct integration of the light curve may not be the best way to compute the pulse energies, since it is likely that not all the nuclear luminosity is variable. In other words, the nucleus may well harbour both a variable and a non-variable component. A non-variable component could be associated with residual starlight from the host galaxy or with a source intrinsic to the AGN. In the latter case, the source could be associated with a nuclear star cluster, with the non-varying portion of the putative accretion disc, or with diffuse emission from the vicinity of the nuclear power-house. The strength of this background component is not directly derivable from the data, but an upper limit to its luminosity is given by the minimum luminosity in the light curve. Subtracting the minimum observed luminosity from the pulse light curves, we find that pulses 70, 81, 88, 90 and 92 enclose B-band energies of 0.36, 0.33, 0.35, 0.51 and 0.33×10^{51} erg respectively. Obviously, both these values and those obtained without the background subtraction are subjected to the uncertainties in the absolute luminosity scales.

If the pattern recurrence suggested by the present analysis is confirmed by further observations, it will be important to investigate its wavelength dependence, particularly in the UV and X-ray regions, where most of the bolometric luminosity of AGN emerges. The detailed evolution of the pulses in different energy bands and the estimation of bolometric energies would provide stringent constraints for possible physical scenarios for the origin of the pulses. The length and sampling rates of the presently available UV and X-ray light curves of NGC 4151 and 5548 do not allow an analysis as detailed as for the optical band, but there is strong evidence that the variations in all these bands are correlated (e.g. Clavel et al. 1992; Edelson et al. 1996), which indicates that the global variability patterns observed in the optical are also present in the UV and X-rays. We note, however, that NGC 5548 is substantially more luminous than NGC 4151 in both UV and X-rays (Perola et al. 1986; Edelson, Krolik & Pike 1990; Clavel et al. 1992; Green, McHardy & Lehto 1993; Korista et al. 1995; Edelson et al. 1996), which indicates that the similarity between absolute luminosities and energies of the pulses identified in the optical light curves of these two galaxies does not hold over a broader frequency range.

4 CROSS-CORRELATION ANALYSIS

The initial method employed to find the pattern coincidences described above was a simple eye inspection of the light curves, a method which, though admittedly subjective, proved quite successful. In this section we assess the statistical significance of these findings.

4.1 Method

Probably the simplest method to identify occurrences of a given pattern in a light curve is first to isolate the pattern we are looking for and then to cross-correlate it with the whole light curve by shifting the pulse along the time axis. High values of the correlation coefficient would then indicate the positions where the pattern fits best, and the statistical significance of the correlation can be easily assessed. To compute such cross-correlations, we first have to consider that the light curves are irregularly sampled. We explored three different techniques to deal with this difficulty: (i) interpolation, (ii) data-windowing and (iii) phase-binning.

Interpolation can be done in one of several ways: interpolating both light curves, interpolating only in the pulse light curve at the dates of the full light curve or vice versa. Any of these alternatives involves some 'data invention', which is particularly critical for NGC 4151, given the long gaps in its light curve.

The second method is, after shifting the pulse to a given date, to find the pulse points within a given time window (say, ± 3 d) around each of the dates of the full light curve. For each date in the light curve we obtained a set of corresponding pulse luminosities which can then be averaged, possibly weighting by their distance to the centre of the window and/or their error bars, to compute the correlation coefficient. Light curve dates which do not have a corresponding pulse point in the time window are excluded from the computation of the correlation coefficient. This method does not involve any interpolation, but it suffers from a more subtle problem. As is evident from the data, the observations are inhomogenously distributed in time. Clustering of the observations around small segments of the light curve (as, for instance, in the 1981.2–1981.7 period in the NGC 4151 light curve) inevitably biases the correlation coefficient, in the sense that instead of measuring the matching of the pulse as a whole it gives a disproportionally large weight to the matching on short time-scales.

The third method ('phase-binning') consists of, after shifting the pulse to a given position in the light curve, binning both pulse and light curve into $\Delta t_{\rm bin}$-wide bins, and correlating the mean values of the two data trains in each of the (non-empty) bins. In this way we solve the problem of overweighting the matching on short time-scales without resorting to interpolation. The size of the bins is dictated by the time-scale to which we want the matching to be measured. As we have seen, there is evidence for pattern matchings on scales of weeks to years, so an appropriate bin size would be of the order of 10 d. The cross-correlations presented below were performed with this method, but we emphasize that, although we judge phase-binning to be superior to interpolation and data-windowing, all three methods were tried and found to give similar results.

4.2 Results

In Fig. 4 we plot the results of the cross-correlation of pulse 90 with the whole light curve of NGC 5548 for a bin size of 5 d. The top panel (a) shows Spearman's non-parametric correlation coefficient ($r_{\rm S}$) as a function of the date to which pulse 90 is shifted. The corresponding confidence level is plotted in panel (b), where, for the sake of clarity, anticorrelations ($r_{\rm S} < 0$) are represented by a negative confidence level. The peak at 1990.2 corresponds to the correlation of pulse 90 with itself, which naturally yields $r_{\rm S} = 1$ and 100 per cent confidence, while the peaks at 1988.1 and 1992.3 correspond to the correlations of pulse 90 with pulses 88 and 92 respectively. It is seen that these coincidences are highly significant (> 99 per cent). This is better seen in panel (c), where we plot the number of standard deviations by which the 'sum of squared differences of ranks' deviates from its expected value in the case of no correlation (see Press et al. 1991). The sign convention here is as in panel (b). Fig. 4(c) shows that the correlation of pulse 90 with pulse 88 is significant to a 4σ level, while pulses 90 and 92 correlate even better (6σ). The mathematical analysis thus corroborates our visual identification of pulse matchings in the light curve of NGC 5548.

Notice that the 1988.1, 1990.2 and 1992.3 peaks are surrounded by adjacent troughs, where the anticorrelations are as significant as in the positive peaks. Strong anticorrelations occur whenever the pulse is shifted by $\sim \pm$ half its duration from one of its matching dates, i.e., as it moves 'off-phase' by 1/2. The situation here is analogous to what would happen if we correlated one cycle of a sine wave with a long sinusoidal light curve: positive peaks would indicate matching phases, and negative peaks would correspond to locations where the pulse phase is offset by 180° with respect to the light curve.

Fig. 5 shows the cross-correlation of pulse 81 with the full light curve of NGC 4151 for $\Delta t_{\rm bin} = 15$ d. The noisier appearance of this plot compared to Fig. 4 is mainly due to the worse sampling rate in NGC 4151 (an average of one observation every 10 d, compared to one every 3 d for NGC 5548). Still, significant peaks are found at the following dates: 1970 (4σ), 1977 (4σ), 1978.8 (3σ) and 1984 (3.5σ), while the maximum at 1981.7 marks the correlation of pulse 81 with itself. Note that, with the exception of 1984, these dates are very similar to those identified visually (Section 3.4). What the cross-correlation is detecting in the 1984 peak is the long-term matching of pulse 81 with the gradual increase in luminosity during the 1984–1985.5 period and the subsequent decrease until 1986.6. Although the long-term agreement is reasonable, the evidence for matching on shorter time-scales is not compelling, as indeed is the case for the 1977 and 1978.8 events. The broad hump in the cross-correlation between 1972 and 1974 corresponds to the region where, as argued above, a superposition of two pulses might have occurred. The significance of the hump is not large ($< 3\sigma$), but this is not surprising, since a single pulse can only partially match the combination of two events. The most significant peak in Fig. 5 (that at 1970) corresponds to the matching between pulses 70 and 81 discussed in Section 3.3. On the whole, it is reassuring to note that the highest peak in the cross-correlation analysis corresponds to the most interesting matching found in our visual analysis of NGC 4151, and that other peaks also coincide with visually estimated possible matchings dates.

Cross-correlations like those performed above but using Pearson's linear correlation coefficient instead of the (more robust) rank-order coefficient yield nearly identical results.

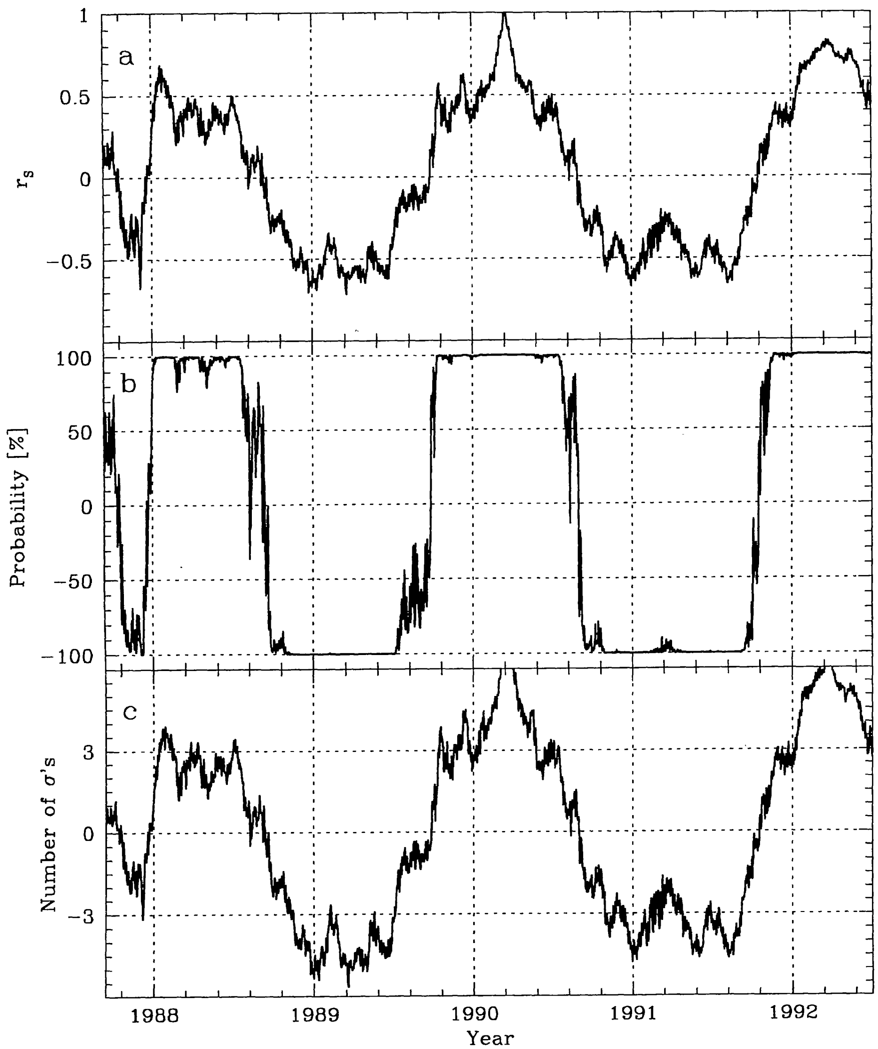

Figure 4. Cross-correlation of pulse 90 with the full light curve of NGC 5548. (a) Spearman's rank correlation coefficient, (b) confidence level of the correlation, and (c) number of standard deviations by which the 'sum of squared differences of ranks' deviates from the expected value in the null hypothesis (no correlation). The sign convention in panels (b) and (c) is that positive peaks correspond to positive correlations and vice versa. High peaks indicate possible fitting dates for pulse 90.

We have also correlated pulses 92 and 88 with the full NGC 5548 light curve, and pulse 70 with NGC 4151. Not surprisingly (given the similarity of the pulses), very similar results were obtained. Finally, we remark that the cross-correlations presented above are not strongly influenced by the bin size chosen. The main effect of $\Delta t_{\rm bin}$ is to determine the smoothness of the cross-correlation functions (small bins leading to 'noisier' curves and vice versa). The significance of the peaks is only marginally affected by the bin size, while their locations remain unchanged. The smaller bin size used for NGC 5548 reflects the much better sampling of the AGN Watch light curve compared to that of NGC 4151. This better sampling allows us to measure the pattern matching in more detail than for NGC 4151.

To conclude, the cross-correlation analysis confirmed the pulse identifications of Section 3. A much more direct and stringent test of the hypothesis that variability patterns such as those proposed here occur recurrently in type 1 Seyfert nuclei will soon be provided by the release of the latest AGN Watch data for NGC 5548. Meanwhile, a further test of the similarities between pulses 88, 90 and 92 could be carried out comparing their spectral properties (colours, line profiles, line ratios), something which can be done with the currently available data.

5 DISCUSSION

The basic temporal structure of pulses 70, 81, 88, 90 and 92 consists of a short, not very energetic burst (subindex 1 in Fig. 3b) followed by a $\sim$2-yr-long powerful burst which shows a global decay with secondary peaks associated with $\sim$ month-scale oscillations (subindices 2–4 in Fig. 3b). This is obviously a simplified description of the structure of the pulses, but it accounts for the most energetic events in the pulse evolution. High-frequency variations are also present, but these are usually of low amplitude (Lyutyi et al. 1989; Dultzin-Hacyan et al. 1992; Edelson et al. 1994, 1996; Gopal-Krishna, Sagar & Wiita 1995).

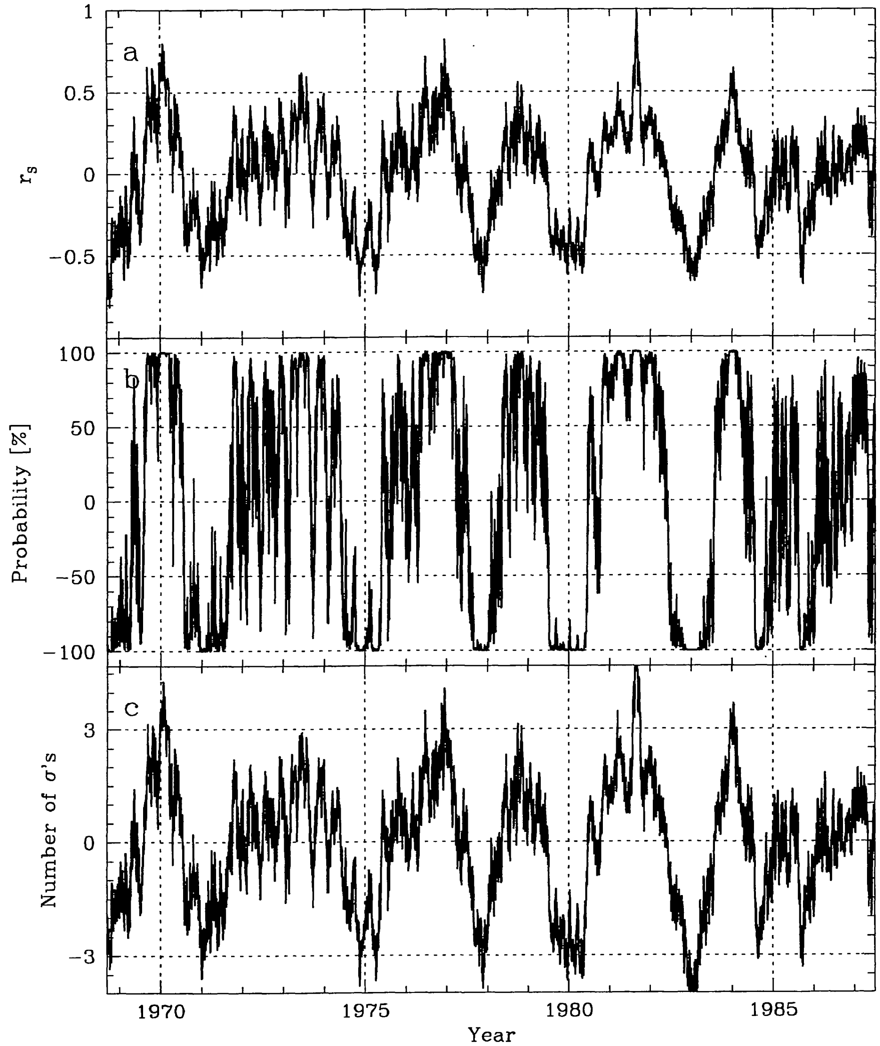

Figure 5. As Fig. 4, but for the cross-correlation of pulse 81 with the light curve of NGC 4151.

Despite their similarities, it is clear that the pulses are not identical. This, however, is not surprising, since an exact repetition of a given pattern would only occur if the physical conditions under which they were generated were identical, an extreme requirement in any physical scenario. The fact that the observed pulses are so similar suggests that their fundamental parameters are similar for all the pulses in both NGC 4151 and 5548. It is interesting to note a similar pattern of variations has been observed in the Hα light curve of NGC 1566 (Alloin et al. 1986), but the time-scale of the slow component there seems to be longer.

5.1 Origin of the pulses

If variability does follow a certain characteristic pattern, the next question is what causes it. In this section we discuss possible interpretations in the context of current AGN theories.

The conventional wisdom is that AGN variability is the result of instabilities in an accretion disc around a supermassive black hole (e.g. Rees 1984; Abramowicz 1991). An important question in this respect is whether such instabilities should produce well-defined patterns at all – theorists are strongly encouraged to address this point. A variability pattern could perhaps be associated with the evolution of an instability as it spirals inwards to be finally accreted by the hole, but this interpretation has to await detailed modelling.

Recurrent patterns find a natural interpretation in models that attribute the luminosity variations to stochastic occurrences of some basic physical process. The best studied example of a model fitting this general scenario is the so-called starburst model for AGN, which attributes the variations to supernova (SN) explosions and their associated compact remnants in a massive young star cluster (Terlevich et al. 1992, 1995; Aretxaga & Terlevich 1994). The starting shot would correspond to the SN flash, while the subsequent long flare and its oscillations are explained in terms of the evolution of the corresponding compact SN remnant (see the comparison of pulse 70 with SNe light curves in fig. 1 of Aretxaga & Terlevich 1994). In fact, hydrodynamical simulations of SN remnants evolving in high-density media produce light curves which resemble those in Fig. 3 (Plewa 1995; Terlevich et al. 1995). This model makes specific predictions about the spectral properties and the different lags between continuum and line variations for different flares. In particular, if the identification of the starting shots as SN flashes is correct, the nuclear spectra show spectral signatures of type II SNe at the corresponding dates.

Another process which might promote variability is the tidal disruption of stars by the gravitational field of a black hole (Rees 1988; Evans & Kochanek 1989; Eracleous, Livio & Binnette 1995), an idea recently discussed in connection with the Hα variations of LINERs such as NGC 1097 (Storchi-Bergmann et al. 1995) and M81 (Bower et al. 1996). Intuitively, one would expect that different disruption events would go through similar evolutionary phases, perhaps leading to a recurrent pattern of variations.

This discussion illustrates the importance of establishing whether AGN variability follows well-defined, recurrent patterns. Empirical confirmation of a pattern would pose a strong constraint on theoretical models, challenging them to match the observations quantitatively. On the other hand, the absence of recurrent patterns could be used to argue against models where the variations are explained in terms of stochastic occurrences of the same type of event.

5.2 Connection with QSO variability

As fundamental as the question of whether AGN variability follows well-defined patterns is the question of whether the variations are due to a Poissonian ('Christmas-tree') type of process. This latter point has been extensively discussed in relation to the variability of QSOs. In a Poissonian process variability is the result of the random superposition of independent pulses. Such a process would result in a '$1/\sqrt{N}$' anticorrelation between the net rms variability and the mean luminosity. Observational studies of the variability–luminosity relationship in QSOs indicate that the slope of the anticorrelation is not as steep as $-1/2$ (Pica & Smith 1983; Hook et al. 1994; Paltani & Courvoisier 1994; Cristiani et al. 1996). Such studies are, however, plagued by photometric and sampling uncertainties as well as redshift effects. When these effects are taken into account, the data are found to be consistent with the Poissonian model (Cid Fernandes 1995; Cid Fernandes, Aretxaga & Terlevich 1996; Aretxaga, Cid Fernandes & Terlevich 1997). Furthermore, a $1/\sqrt{N}$ law applies only if the energies and time-scales of the pulses do not depend on the QSO luminosity (Cid Fernandes et al. 1996). Though far from being confirmed, a Poissonian nature for the variations observed in QSOs is by no means ruled out by the currently available data.

If QSO light curves are indeed the result of the random superposition of many pulses like those identified in the light curves of NGC 4151 and 5548, then their structure function (SF) should be equal to the SF of the individual pulses. The SF at 'lag' τ is defined as the mean value of $[L(t+\tau)-L(t)]^2$ over the light curve, being basically an 'upside-down' version of the auto-correlation function. The SF is particularly useful in picking up variability time-scales. The *ensemble* SF of large QSO samples (e.g. Hook et al. 1994; Cristiani et al. 1996) shows a rapid rise for lags shorter than ~ 2–3 yr and then flattens to a roughly constant level, indicating that the duration of the pulses is ~ 2–3 yr. This is comparable to the durations of pulses 70, 81 and 90, whose SF is plotted in Fig. 6.

Regarding the energy of the pulses, Cid Fernandes et al. (1996) and Aretxaga et al. (1997) have shown that if QSO variability results from a Poissonian process, then the *B*-band energy of the individual pulses must be of the order of 10^{50}–10^{51} erg. These values are in excellent agreement with those derived in Section 3.5 (see also Aretxaga & Terlevich 1993, 1994), strengthening the idea that such pulses constitute a 'unit' of variability in active galaxies.

6 CONCLUSIONS

We have reported the apparent existence of a recurrent pattern in the optical light curves of NGC 4151 and 5548. This pattern consists of a short, not very energetic burst

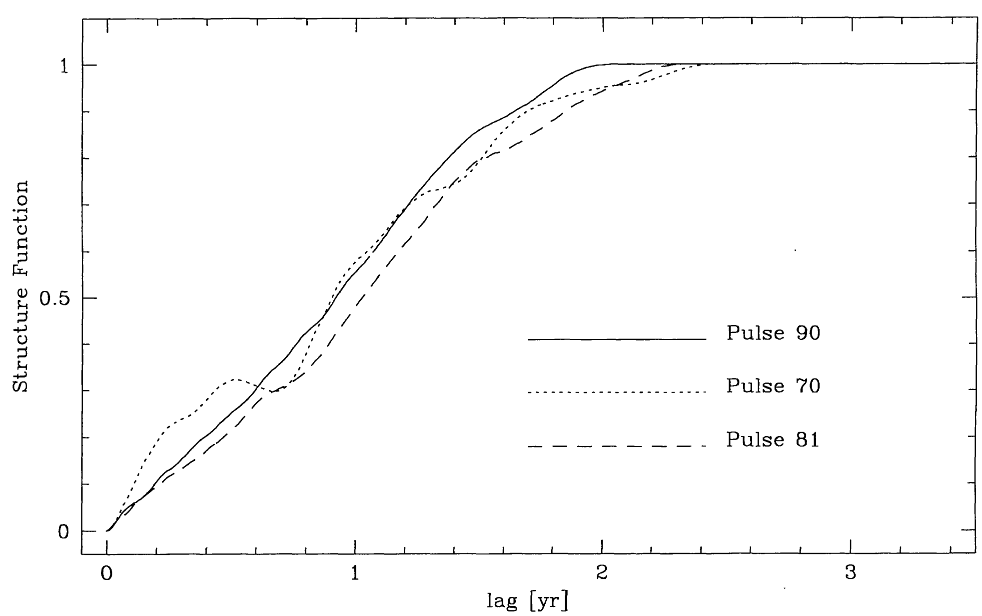

Figure 6. Structure functions of pulses 70, 81 and 90, normalized to their asymptotic limit.

followed by a long, powerful one which shows a global decay with month-scale oscillations. Possible interpretations in terms of accretion disc instabilities, supernovae and stellar disruptions were briefly outlined. A possible connection with the variability properties of QSOs was also discussed. We found that the energies and time-scales of the pulses identified in NGC 4151 and 5548 are consistent with those derived from QSO light curves under the assumption that QSO variability is the result of a Poissonian process.

The evidence, though suggestive, has to be taken with caution, given the difficulties associated with the irregular sampling in the present data sets. Continuing monitoring of these two sources and other low-luminosity AGN will certainly be able to establish conclusively whether the suggested pattern is real or just a rare coincidence.

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