Colour changes in quasar light curves

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ABSTRACT

The study of quasar variability has long been seen as a way to understanding the structure of the central engine of active galactic nuclei, and as a means of verifying the morphology of the standard model. Much work has already been done on the statistical properties of light curves monitored in one colour, and it is now possible to use these observations to test predictions of theoretical models. The addition of a second colour can add enormously to the power of such tests, and put tight constraints on the nature of the variations. In this paper a yearly monitoring programme of several hundred quasars in blue and red passbands covering 21 years is presented. The statistics of colour changes are examined for a 15 year period of homogeneous data with Fourier power spectrum analysis, in a form suitable for testing against theoretical predictions. The results of the Fourier analysis show that there is more power in blue light on all timescales than in the red. Examination of the light curves shows several different modes of colour change. However, if allowance is made for the effects of the underlying host galaxy, the variations become close to achromatic. There are however structural differences between red and blue light curves which cannot be accounted for in this way, and various modes of variability including disc instability and microlensing are examined to provide explanations for these features.

Key words: quasars: general – galaxies: active

1 INTRODUCTION

It has long been recognised that the variability of active galactic nuclei (AGN) has the potential to probe the structure and dynamics of the central engine and put tight constraints on any unified model. For low luminosity AGN (Seyfert galaxies) extensive monitoring of short term photometric and spectroscopic variations (Peterson et al. 1999) has made a major impact on the understanding of the structure of the central regions. Much effort has also been put into the optical monitoring of luminous AGN (quasars) (Hook et al. 1994; Cristiani et al. 1996; Hawkins 1996), but with less concrete results. The main problems have been the long time scales over which quasars appear to vary making uniformly sampled light curves for a large number of objects very hard to obtain, and the lack of theoretical predictions against which to test models of quasar variability. A first step towards rectifying this was made possible by the publication of predicted structure functions for light curves in accretion disc and starburst models of quasar variability (Kawaguchi et al. 1998). The predictions were made for one colour passband, and were suitable for comparing with structure functions for samples of quasar light curves. What was needed was a sample of several hundred quasars covering a wide range of redshifts and luminosities, regularly monitored over a period of decades. Such a sample has gradually been built up from plates taken with the UK 1.2m Schmidt telescope in the ESO/SERC field 287, details of which are given in the following section. Light curves from these data, together with theoretical predictions for the structure function of variations, have been used in a recent paper (Hawkins 2002) to distinguish between various models of AGN variability. An unexpectedly complicated picture emerged in which Seyfert galaxy variations were best explained by an accretion disk model, while quasar variability was closer to the predictions for microlensing.

A new dimension can be added to the existing analysis by the addition of a second passband to the monitoring data. Different models of variability show very different behaviour in the way colour changes manifest themselves in the light curves. So far, quantitative predictions suitable for testing against observations have not been published for any models, but even so there are generic expectations for colour effects in the best studied models. For example, in the starburst model for AGN variability (Aretxaga & Terlevich 1994), the variations are attributed to successions of supernova explosions. In this model one can confidently predict that AGN will become bluer as they get brighter, just as supernovae do.
Figure 1. Light curves in $B_J$ (filled circles) and $R$ (open circles) for a selection of quasars which show no systematic colour change with brightness.

Observational work on colour changes in AGN is rather sparse. The long term monitoring programme of the Seyfert galaxy NGC 5548 has shown strong colour changes in the ultraviolet from IUE observations (Clavel et al. 1991). This is illustrated in Fig. 3 of Hawkins & Taylor (1997) which shows the data uniformly sampled and converted to a magnitude scale. The situation with regard to quasars is less clear. Hawkins (1996) concluded that light variations in most quasars were close to being achromatic, on the basis of an analysis of correlations between yearly changes in $B_J$ and $R$ magnitudes, but Cristiani et al. (1997) claimed to find a difference in the amplitude of structure functions for $B$ and $R$ band light curves. A similar small effect is seen in Fourier power spectra (Hawkins 2001), but in these data the author concludes that the difference is not significant.

In this paper the intention is to improve on these earlier results by carrying out a comprehensive analysis of colour changes in quasar light curves. This will provide a powerful discriminant between quasar models as they become sufficiently robust to make testable predictions.

2 THE QUASAR MONITORING PROGRAMME

The light curves in this study are from a long term quasar monitoring programme based on photographic plates taken with the UK Schmidt Telescope of the ESO/SERC field 287. The field centre is at $21h 28m, -45^\circ$ (1950), and some 350 sky limited plates and films have been taken over a variety of timescales from hours to 26 years, and in several optical passbands. Of particular relevance to the present programme is a yearly sequence of observations in $B_J$ (IIIa-J emulsion with a GG395 filter) and $R$ (IIIa-F or 4415 emulsion with a RG630 filter) passbands covering 21 years from 1980 to 2001. This unbroken sequence normally included 4 sky limited exposures in both $B_J$ and $R$ each year, but in a few years it was only possible to obtain one plate in one or both of the passbands. Details of all the plates used in this paper are given in Table 1 of the Appendix. The early plates (up to 1992) were measured with the COSMOS measuring machine, and after that with SuperCOSMOS at the Royal Observatory, Edinburgh. The survey area was confined to
Figure 2. Light curves in $B_J$ (filled circles) and $R$ (open circles) for a typical selection of quasars. The variation is largely achromatic.
a square area of 19 deg$^2$ in the centre of the field to avoid problems with vignetting and other off-axis effects. Approximately 180,000 objects were detected in this area to a limit of $B_J \approx 21.5$. The $R$ plates went to a limit of $R \approx 20.5$.

The plates were paired up to give around 100 photometric measures in each of $B_J$ and $R$ for every object on the plate where a detection was made. Because variability was the main interest for these data, the measures were first reduced to a common photometric zero point using local standards. These transformed measures were then calibrated with a CCD standards (Hawkins 1996), giving a typical relative photometric error of 0.08 mag for each plate. For most years where 4 plates were available this error reduced to 0.04 mag. A more detailed discussion of these errors is given by Hawkins (1996) and references therein. The absolute photometric error of 0.08 mag for each plate. For most years where 4 plates were available this error reduced to 0.04 mag. A more detailed discussion of these errors is given by Hawkins (1996) and references therein. The absolute photometric errors across the field are somewhat larger than this, but are hard to pin down precisely without a grid of standards covering the whole field. They are however not significant for the present investigation where relative change in brightness is being analysed.

The quasars for the sample were selected by a number of methods including ultra-violet excess, variability, objective prism, and red drop-out. Of the estimated 1800 quasars in the field, some 1200 now have redshifts in the range $0.1 < z < 4.5$. From this parent population a number of complete samples have been constructed according to well-defined selection criteria (Hawkins 2000). The light curves now span 26 years in the $B_J$ and $R$ magnitude, being measured at every 0.35 mag, the threshold for detection by variability. The statistics of this are discussed in more detail by Hawkins (2000). The quasar light curves in this survey appear to be most useful on a timescale of 5 years or more. Short term variations were studied by taking 16 exposures over six months in 1984. Typical light curves are illustrated by Hawkins (1996), and analysis shows that very few of the quasars in the sample vary by more than 0.1 mag over this period. This is too close to the photometric errors on the measurements to be useful for statistical analysis. In fact the median amplitude for quasar variation is about 0.6 mag, and most quasars in the sample take a few years to achieve this (Hawkins 2000).

3 COLOUR CHANGES IN QUASAR LIGHT CURVES

3.1 Qualitative aspects of the light curves

It was stated by Hawkins (1996) that the variation of most quasars appears to be nearly achromatic, and indeed it is not difficult to find examples of quasar light curves which show no measurable colour change even with large changes in amplitude. Four such cases are shown in Fig. 1, and it will be seen that although there is some scatter between blue and red magnitudes in individual years, there is no systematic change in colour with brightness. At the other extreme, there are quasars which show light curves of very different character in blue and red passbands (Hawkins 1998).

The long term (several years) variation of most quasars is near to being achromatic, but close examination of the light curves shows small departures from this simple picture. Fig. 2 shows six typical quasar light curves which illustrate this. It will be seen that although there is no systematic colour change between maximum and minimum brightness, sharp features in the blue light curves tend to be slightly ‘smeared out’ in the red. Also, there are occasional small isolated fluctuations on a timescale of a year in either passband which are not mirrored in the other colour. One type of variation which is rarely seen in the quasar population is the strictly chromatic variability observed for NGC 5548 (Clavel et al. 1991).

3.2 Fourier power spectra of the light curves

Most statistical analysis of AGN light curves until recently was carried out by calculating the structure function (Cristiani et al. 1996; Hook et al. 1994) or auto-correlation function (Hawkins 1996). The idea was to characterise the timescale or amplitude by reference to the shape of these functions, but the early results did not shed much light on these or any other parameters. There were several problems to overcome. Perhaps the most important one concerns the timescale covered by the observations. Inspection of the light curves in Figs 1 and 2 strongly suggests power on a timescale of decades or more, and recent work has confirmed this (Hawkins 2001). To properly measure the timescale of variation it is clear that a run of data covering many tens of years is ideally needed. Although this ideal has yet to be achieved, the survey on which the present analysis is based goes a long way to addressing the problem. Another problem with early datasets was the lack of homogeneous, regular monitoring. Without this, time series analysis becomes difficult, with spurious features and aliasing dominating the results. It is also important to have a large sample of light curves covering a large span of AGN redshift and luminosity to enable subsamples to be analysed and compared. Again, this survey marks a major improvement on earlier work.

Another area of difficulty concerns the procedures which have been used to analyse light curves. The irregular pattern of observations in the monitoring programmes has led to the choice of structure or auto-correlations functions as analytical tools, which are relatively insensitive to aliasing problems from unevenly spaced data. However, these functions have a number of drawbacks, including correlation between the points, difficulty in characterising the errors, and ambiguity of interpretation. Fourier power spectra, although containing essentially the same information for an infinite run of data, provide a number of advantages for finite datasets. The frequency values are much less affected by neighbouring points, the errors are relatively easy to calculate, and the interpretation is much more straightforward than for other functions. The main reason that they have not been used in the past is that to be useful a long run of evenly sampled homogeneous data is essential to avoid insurmountable aliasing problems. The data described in section 2 now meet these requirements, and so we shall use Fourier power spectrum analysis to investigate the chromatic properties of AGN light curves in this paper.

We define the Fourier power spectrum $P(j)$ for each light curve, in the observers frame, as...
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3.3 Effect of an underlying host galaxy

One obvious possible reason for a change in colour as AGN vary is the presence of an underlying galaxy of comparable brightness to the nucleus, but of a redder colour. When the nucleus is at its brightest, the additional light from the underlying galaxy will have little effect on either the blue or red light curves. However, as the nucleus dims the light of the quasar will become progressively more dominated by the light of the underlying galaxy. For a red galaxy this will happen first in the red, and the red light curve may even bottom out at the $R$ magnitude of the underlying galaxy. In blue light the quasar will continue to fade, as the nuclear light continues to dominate the faint $B$ flux of the galaxy. Plausible examples of this process may be seen in Fig. 3 which shows the light curves for two low luminosity AGN ($M_B \sim -22$). This pattern of behaviour is never seen in more luminous AGN (quasars) such as in Fig. 1.

The possibility that colour changes in light curves are caused by the effects of an underlying galaxy can be tested by attempting to correct for such an effect. The first step is to estimate the mean magnitude of the quasar host galaxies and its dispersion. This can be done for the quasars in the sample used here by looking for light curves similar to those in Fig. 3 which bottom out in the red, but continue falling in blue. A sample of 17 was chosen by eye from the available quasar light curves, on the basis that they showed clear signs of the variation in $R$ reaching a minimum when the $B_J$ light continued to fade. The mean luminosity of the underlying galaxies measured in this way was found to be $M_R = -22.6$ with a standard deviation $\sigma = 0.4$.

The small dispersion in the flux of host galaxies provides a plausible basis for attempting to correct for the colour distortion of the light curves by subtracting the mean value from each point in the $R$ band light curves. The effect of doing this is shown in Fig. 4. Light curves for two quasars showing evidence for colour changes with luminosity are shown in the two left hand panels. The colour change is such that the amplitude in $B_J$ is larger than in $R$. The same light curves are shown in the two right hand panels, but with the estimated mean flux of the underlying galaxy subtracted. It will be seen that apart from one or two isolated short term fluctuations the variation is now close to being achromatic in both light curves.

The two galaxies in Fig. 4 were chosen so that the effect is clear to the eye, but there is also a significant effect on the

\[
P(j) = \left( \sum_{n=0}^{N-1} \cos \left( \frac{2 \pi j n}{N} \right) m(n) \right)^2 + \left( \sum_{n=0}^{N-1} \sin \left( \frac{2 \pi j n}{N} \right) m(n) \right)^2
\]

where $N$ is the number of epochs, and the frequency $j$ runs from 0 to $N-1$. The power spectrum of a sample of light curves is defined as the mean of the individual power spectra $P(j)$.

Fig. 5 shows the combined Fourier power spectrum for a sample of 302 blue and red passband light curves for the period 1983-1987. During this period there were four plates of similar quality in both colours taken within a few weeks of each other every year. COSMOS measures of the four yearly plates in each colour were averaged with equal weight to give a uniformly sampled and homogeneous run of data. The power spectrum was evaluated for each light curve, and these power spectra were then averaged as described above. The errors were calculated in two ways. Firstly, the sample was split into various subsamples, and the dispersion in the resulting power spectra used to estimate the errors. Secondly, a sample of stars from the same set of measurements as the quasars was analysed in the same way, and the dispersion in the frequency measures used to estimate the error on each point. The errors obtained by these two methods were not significantly different, and an average value was used. The left hand panel shows data for the observed light curves, and it will be seen that in both $B_J$ and $R$ passbands the shape of the power spectrum is close to a power law, and although the two slopes are similar there is significantly more power in $B_J$. This implies a larger amplitude of variation in blue light, and hence that the AGN become bluer as they brighten.
Figure 4. Light curves in $B_J$ (filled circles) and $R$ (open circles) for two AGN. The left hand panels show the light curves as measured, with evidence for chromatic variation. In the right hand panels the contribution from the underlying galaxy has been subtracted, and the variation is close to being achromatic.

statistical properties of variation when the correction is applied to a large sample of light curves. The right hand panel of Fig. 5 shows the power spectrum for the sample of 302 light curves in the left hand panel, but with the contribution of the underlying galaxy subtracted as described above. It is clear that in the right hand panel the two power spectra are indistinguishable within the errors, implying that the residual variation is close to achromatic. We can examine this model in a bit more detail by splitting the sample into low and high luminosity objects to see whether a single luminosity for the underlying galaxy really is sufficient. In Fig. 6 we see power spectra as for Fig. 5, but in two luminosity bins containing 125 and 177 light curves for low and high luminosity quasars respectively. In each case a galaxy luminosity of $M_R = -22.6$ has been used, and it is clear that for the less luminous quasars this works well. For the more luminous quasars a somewhat brighter underlying galaxy would be needed to produce achromatic variation.

3.4 Colour changes in accretion discs

In most well studied systems which are believed to be powered by accretion discs, variations in brightness are accompanied by colour changes. These are usually such that the object becomes bluer with increasing luminosity. Well known examples of this come from dwarf novae (Horne et al. 1990) and Seyfert galaxies (Clavel et al. 1991; Peterson et al. 1999). The development of accretion disc models has not so far reached the point where quantitative predictions suitable for comparing with observations have been made as to the nature of colour changes, so in interpreting observed colour changes it is necessary to rely on more general conceptual considerations.

The standard model of a geometrically thick, optically thick disc (Shakura & Sunyaev 1973) has a temperature gradient such that it becomes cooler and redder with increasing radius. It is not perhaps surprising that it can be shown that the non-linear oscillations of such a disc can lead to temperature and hence colour changes. Radial temperature changes...
in thermally unstable slim accretion discs have been examined in some detail with the aid of numerical simulations by Honma et al. (1991). They show that a hot wave propagates outwards as instabilities occur in the inner disc, leading to a change in integrated colour, in the sense that as the disc becomes brighter it becomes bluer. This is consistent with the observations of Seyfert galaxies (Clavel et al. 1991; Peterson et al. 1999), and also for the type of quasar variation seen in Fig. 4. The achromatic variation seen in Fig. 1 would not be consistent with this model, and nor would the light curves shown in Fig. 2. Here, basically achromatic variation is modified by the smoothing out in the red of the sharper features in the blue light curves.

An alternative approach to modelling optical variability in accretion discs (Mineshige et al. 1994) invokes a cellular automaton mechanism. The accretion disc achieves a self-organised critical state in which a $1/f$ spectrum of fluctuations is produced. This cellular automaton model appears to be the most promising approach to modelling disc instabilities at the moment. It has been developed by Kawaguchi et al. (1998) to investigate variability in AGN. They use it to produce simulated light curves with a power law spectrum of variations which can be compared with observations (Hawkins 2001). For Seyfert galaxies there is good agreement, although for more luminous quasars the observed spectrum of variations is flatter. Although no quantitative predictions have so far been made for colour changes, it is plausible that in a disc with a strong temperature and hence colour gradient these avalanches will produce chromatic effects as the flux varies. The problem here is that any variability would be on a very short timescale, and inconsistent with the observations of optical variations. Definitive answers to these points must await model predictions for colour changes in the different types of accretion disc.

### 3.5 Colour changes from microlensing

An alternative explanation for the effects shown in Fig. 5 comes from microlensing. In this picture, the observed variation is produced by the gravitational microlensing effect of a population of planetary or sub-stellar mass bodies along the line of sight to the quasar (Hawkins 1996). Although the microlensing of a point source produces a strictly achromatic light curve, for an accretion disc with a radial temperature gradient this is not necessarily so. For example, if the nucleus is a compact blue source unresolved by the characteristic mass of the microlenses, but in the red the source is less compact and partially resolved by the lensing objects, colour changes may be observed as the source is microlensed. The effect of this can be seen in the results of numerical simulation of microlensing of unresolved and partially resolved sources (Lewis et al., 1993; Schneider & Weiss 1987) where the smaller power for the resolved sources is well illustrated. The application of this model to the microlensing of an accretion disc with a compact blue nucleus and a strong radial colour gradient would be to produce less power in the red than the blue fluctuations, providing that the emitting region of the disc is comparable with the Einstein radius of the lenses.

These ideas have been put on a firmer and more quantitative footing in a recent paper by Yonehara et al. (1999). They carry out numerical simulations of the microlensing
of accretion disks by a compact body, and show that for a standard optically thick accretion disc with a radial temperature gradient colour changes will be seen, whereas for an optically thin (advection dominated) disc where most of the emission takes place at the inner edge, the variation will be achromatic. Yonehara et al. (1999) base their modelling on the multiply lensed quasar system Q2237+0305. The individual images in this system have been shown to vary achromatically when microlensed (Corrigan et al. 1991; Houde & Racine 1994) which would imply an optically thin disc. How-

**Figure 6.** Fourier power spectra for quasar light curves in $B_J$ (filled circles) and $R$ (open circles). The left hand panels show results for the observed light curves, in two luminosity bins. The right hand panels show Fourier power spectra for the same light curves, after subtracting a contribution for the underlying galaxy of absolute magnitude $M_R = -22.6$ in both luminosity bins.
ever, to account for the colour changes implied in Fig. 5 and illustrated in the light curves, an accretion disc of greater optical depth would be required.

There is one other aspect of microlensing which has relevance to the quasar light curves, especially those in Fig. 2. In a situation where the accretion disc has a blue compact core embedded in redder outerparts, then lensing can produce cusp-like features from the unresolved central region which are smoothed out in the resolved red light source. The idea can be seen from the synthetic light curves for more and less resolved sources in Schneider & Weiss (1987). This provides an explanation for the way sharp blue features become smoother in the red in Fig. 5.

4 DISCUSSION

It is clear from examination of Figs. 1-4 that colour changes can occur in quasar light curves. This result is consistent with earlier work for Seyfert galaxies (Clavel et al. 1991) and quasars (Cristiani et al. 1997), but also shows that there are apparently different modes of colour change. We tentatively identify the following patterns:

(i) Achromatic, no indication of any colour change.
(ii) Light curves showing the same structure in red and blue, but with a scale change.
(iii) The apparent bottoming out of red light curves as blue light continues to decline.
(iv) Colour change mainly characterised by the smoothing in the red of sharp features in the blue.

It is quite possible that no single model will be found that can account for such a diverse range of features in the light curves. On the other hand, theories of quasar variability should make predictions about colour changes, which may well be similar and require detailed comparison with good data to distinguish them. Fig. 5 implies that even with a very simple model for the underlying galaxy, the mean power spectra for red and blue light can be brought into coincidence.

Although it is clear that the presence of an underlying red galaxy plays a significant role in AGN colour changes, it cannot account for all the features seen in the two-colour light curves. Examination of Fig. 2 shows that there are features in the light curves which cannot be reconciled in this way. To be more specific, certain cusp-like features in the blue light curves appear as if smoothed out in the red. Furthermore, the larger the colour change, the more pronounced this smoothing will be.

5 CONCLUSIONS

In this paper we have investigated colour changes in a large sample of quasars, monitored yearly in the \(B\) and \(R\) bands over a period of 21 years. Examination of the light curves suggests that the variations involve colour changes for many quasars, and Fourier power spectrum analysis for a 15 year homogeneous subset of the data confirms that there is more power on all timescales in the blue passband compared with red. This effect may at least in part be due to the contribution of red light from the underlying host galaxy, and can be corrected for in such a way that the variation comes close to being achromatic for all quasars.

Current theories of accretion disc instability can explain colour changes seen in observations of Seyfert galaxies. The standard optically thick accretion disk is characterised by a radial temperature gradient which when perturbed will tend to exhibit changes in integrated colour. However, they do not appear to be able to produce the smearing out in the red of blue features which is a characteristic of many quasar light curves.

An alternative explanation for the observed variability of quasars is that it is caused by the microlensing effects of a population of planetary or sub-stellar mass bodies distributed along the line of sight. In this case achromatic variation can be accounted for by microlensing of an optically thin (advection dominated) disc. Chromatic variations are possible with a conventional optically thick disc with a radial colour gradient, which is large compared with the Einstein radius of the lenses. This can also explain the observed smearing out in the red of cusp-like features in the blue.

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APPENDIX

Table 1. Details of photographic observations for the two-colour monitoring programme

| Plate | Date     | Emulsion | Filter | Exposure |
|-------|----------|----------|--------|----------|
| R 6196| 80-08-04 | IIIaF    | RG 630 | 90.0     |
| R 6200| 80-08-05 | IIIaF    | RG 630 | 90.0     |
| R 6209| 80-08-06 | IIIaF    | RG 630 | 90.0     |
| J 6229| 80-08-09 | IIIaJ    | GG 395 | 65.0     |
| R 6230| 80-08-10 | IIIaF    | RG 630 | 90.0     |
| J 7099| 81-08-01 | IIIaJ    | GG 395 | 75.0     |
| R 7259| 81-10-06 | IIIaF    | RG 630 | 15.0     |
| R 8005| 82-08-14 | IIIaF    | RG 630 | 90.0     |
| R 8009| 82-08-16 | IIIaJ    | GG 395 | 60.0     |
| R 8649| 83-07-09 | IIIaF    | RG 630 | 90.0     |
| R 8671| 83-07-14 | IIIaF    | RG 630 | 90.0     |
| R 8717| 83-08-03 | IIIaF    | RG 630 | 90.0     |
| R 8723| 83-08-04 | IIIaF    | RG 630 | 90.0     |
| J 8727| 83-08-05 | IIIaJ    | GG 395 | 65.0     |
| J 8728| 83-08-05 | IIIaJ    | GG 395 | 65.0     |
| J 8729| 83-08-05 | IIIaJ    | GG 395 | 65.0     |
| J 8730| 83-08-05 | IIIaJ    | GG 395 | 65.0     |
| J 9322| 84-05-26 | IIIaJ    | GG 395 | 60.0     |
| R 9323| 84-05-26 | IIIaF    | RG 630 | 80.0     |
| J 9327| 84-05-27 | IIIaJ    | GG 395 | 60.0     |
| J 9335| 84-05-28 | IIIaJ    | GG 395 | 60.0     |
| R 9336| 84-05-28 | IIIaF    | RG 630 | 90.0     |
| J 9338| 84-05-29 | IIIaJ    | GG 395 | 60.0     |
| R 9365| 84-06-03 | IIIaF    | RG 630 | 90.0     |
| R 9374| 84-06-04 | IIIaF    | RG 630 | 90.0     |
| J10260| 85-06-14 | IIIaJ    | GG 395 | 70.0     |
| J10264| 85-06-15 | IIIaJ    | GG 395 | 70.0     |
| J10271| 85-06-16 | IIIaJ    | GG 395 | 70.0     |
| J11344| 86-09-04 | IIIaJ    | GG 395 | 80.0     |
| R11345| 86-09-05 | IIIaF    | RG 630 | 90.0     |
| R11351| 86-09-06 | IIIaF    | RG 630 | 80.0     |
| R11359| 86-09-07 | IIIaF    | RG 630 | 75.0     |
| R11360| 86-09-07 | IIIaF    | RG 630 | 75.0     |
| J11387| 86-09-25 | IIIaJ    | GG 395 | 90.0     |
| R11919| 87-05-25 | IIIaF    | RG 630 | 128.0    |
| J11949| 87-06-04 | IIIaJ    | GG 395 | 75.0     |
| J11971| 87-06-22 | IIIaJ    | GG 395 | 104.4    |
| J12012| 87-07-18 | IIIaJ    | GG 395 | 75.0     |
| J12023| 87-07-22 | IIIaJ    | GG 395 | 28.5     |
| R12084| 87-08-21 | IIIaF    | RG 630 | 130.0    |
| R12136| 87-09-14 | IIIaF    | RG 630 | 130.0    |
| J12602| 88-06-12 | IIIaJ    | GG 395 | 120.0    |
| R12626| 88-06-19 | IIIaF    | RG 630 | 106.1    |
| J12648| 88-07-12 | IIIaJ    | GG 395 | 100.0    |
| J12656| 88-07-14 | IIIaJ    | GG 395 | 100.0    |
| J12657| 88-07-14 | IIIaJ    | GG 395 | 100.0    |
| R12669| 88-07-18 | IIIaF    | RG 630 | 150.0    |
| R12740| 88-09-04 | IIIaF    | RG 630 | 140.0    |
| R12771| 88-10-07 | IIIaF    | RG 630 | 140.0    |
| R13207| 89-07-27 | IIIaF    | RG 630 | 90.0     |
| R13251| 89-08-26 | IIIaF    | RG 630 | 120.0    |
| J13252| 89-08-26 | IIIaJ    | GG 395 | 60.0     |
| J13269| 89-09-03 | IIIaJ    | GG 395 | 65.0     |
| R13270| 89-09-03 | IIIaF    | RG 630 | 75.0     |
| J13315| 89-09-24 | IIIaJ    | GG 395 | 60.0     |
| J13316| 89-09-24 | IIIaJ    | GG 395 | 60.0     |
| R13338| 89-09-28 | IIIaF    | RG 630 | 100.0    |
| J13760| 90-06-23 | IIIaJ    | GG 395 | 60.0     |
| Plate | Date       | Emulsion | Filter | Exposure |
|-------|------------|----------|--------|----------|
| R13767 | 90-06-29   | IIIaF    | RG 630 | 90.0     |
| J13789 | 90-08-19   | IIIaJ    | GG 395 | 60.0     |
| R13790 | 90-08-19   | IIIaF    | RG 630 | 84.2     |
| J13819 | 90-09-10   | IIIaJ    | GG 395 | 60.0     |
| R13830 | 90-09-16   | IIIaF    | RG 630 | 95.0     |
| J13837 | 90-09-17   | IIIaJ    | GG 395 | 65.0     |
| R13909 | 90-10-12   | IIIaF    | RG 630 | 110.0    |
| J13837 | 90-09-17   | IIIaJ    | GG 395 | 65.0     |
| R13909 | 90-10-12   | IIIaF    | RG 630 | 110.0    |
| J13837 | 90-09-17   | IIIaJ    | GG 395 | 65.0     |
| R13909 | 90-10-12   | IIIaF    | RG 630 | 110.0    |
| J13837 | 90-09-17   | IIIaJ    | GG 395 | 65.0     |
| R13909 | 90-10-12   | IIIaF    | RG 630 | 110.0    |
| J13837 | 90-09-17   | IIIaJ    | GG 395 | 65.0     |
| R13909 | 90-10-12   | IIIaF    | RG 630 | 110.0    |
| J13837 | 90-09-17   | IIIaJ    | GG 395 | 65.0     |
| R13909 | 90-10-12   | IIIaF    | RG 630 | 110.0    |
| J13837 | 90-09-17   | IIIaJ    | GG 395 | 65.0     |
| R13909 | 90-10-12   | IIIaF    | RG 630 | 110.0    |
| J13837 | 90-09-17   | IIIaJ    | GG 395 | 65.0     |
| R13909 | 90-10-12   | IIIaF    | RG 630 | 110.0    |
| J13837 | 90-09-17   | IIIaJ    | GG 395 | 65.0     |
| R13909 | 90-10-12   | IIIaF    | RG 630 | 110.0    |
| J13837 | 90-09-17   | IIIaJ    | GG 395 | 65.0     |
| R13909 | 90-10-12   | IIIaF    | RG 630 | 110.0    |
| J13837 | 90-09-17   | IIIaJ    | GG 395 | 65.0     |
| R13909 | 90-10-12   | IIIaF    | RG 630 | 110.0    |
| J13837 | 90-09-17   | IIIaJ    | GG 395 | 65.0     |
| R13909 | 90-10-12   | IIIaF    | RG 630 | 110.0    |