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Rapid infrared spectral variability of 3C 66A in outburst

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Abstract. Infrared observations taken during the major outburst seen in 1993 show strong evidence of rapid variability in 3C 66A on a time scale of a few hours, with associated variability of the spectral slope on the same time scale. A strong ($P \gg 99\%$) correlation is seen between the flux at 2.2 microns and the spectral index, with the spectrum steepening as the flux rises, the opposite trend to that seen normally in blazars. Such rapid variability cannot easily be explained by current relativistic jet models; a better option is black body radiation from hot spots on the accretion disk, possibly linked to strong magnetic fields, although the rapid time scale of the variation and its energetics pose serious problems. One possible solution is to invoke bremsstrahlung radiation from a flare, which is later modified by a high degree of extinction through the disk.

Key words: quasars: 3C 66A – infrared: galaxies – accretion, accretion disks – radiation mechanisms: thermal – radiation mechanisms: non-thermal

1. Introduction

The blazar 3C 66A is one of the prime targets of an on-going major international monitoring effort which was started in 1993 and aims to obtain high quality light curve monitoring of a small sample of objects at a number of optical, infrared and radio frequencies. This monitoring programme was designed to provide a photometric baseline for the *OJ-94* project (see Takalo et al. 1994). Extensive light curves of OJ287 and 3C 66A were obtained during the 1993/94 observing season (see, for example, Sillanpää et al. (1994), Sadun et al. (1994), Kidger et al. (1994a, b), for OJ287; Pursimo et al. (1994), Takalo et al. (1994a) for 3C 66A). 3C 66A was found to be show an unprecedentedly high level of activity during the monitoring, with $V \sim$ 14.0–14.4, more than a magnitude above its normal quiescent level (Kinman 1976; Craine et al. 1975; Wills & Wills 1974; Scott et al. 1976).

Extensive infrared observations of 3C 66A have been carried out at Teide Observatory, Tenerife since 1990 (see: Takalo et al. 1992; De Diego 1994). During these observing campaigns we have made considerable efforts to detect infrared microvariability in 3C 66A and other objects. Intranight infrared variability has not previously been observed in this source, but other blazars such as AO0235+164, OJ287, Mark421, Mark501 and BL Lac have all shown prominent infrared variations on time scales from a few minutes to hours. The observation of very fast variations is important because it provides information on the smallest scale structures within the active nucleus. It has been generally assumed that many of the very fast variations must occur within the central region of the quasar, probably the inner accretion disc (Abramovicz et al. 1992; Carrasco et al. 1985; Vila 1979; Grauer 1984), although there is increasing evidence that, in at least some classes of AGN, a relativistic jet is responsible. The characteristics of the variability provides information on the structure, geometry and conditions in the emitting region. Rapid variability is thus capable of providing a very detailed and searching test of existing models.

Infrared microvariability is of considerable interest for various reasons. Firstly, infrared radiation is of considerably lower energy than optical radiation and thus may probe a different region of the inner core. Secondly, the relative amplitudes of infrared and optical microvariability are strongly model dependent; if a two component model is assumed (eg: a non-variable component such as the background from the host galaxy, or the relativistic jet and a variable component, which might be shocks within the jet, hot spots on the accretion disk, to quote just a very few of the most widely accepted possibilities) the relative contributions of the two components will predict widely differing amplitudes of variability at different frequencies. As the differences between the frequencies of adjacent bands are proportionately much greater in the infrared to the visible, the infrared is particularly suited to the detection of individual components.

2. Observations and reduction

The observations were taken with TIRGO (Telescopio InfraRosso del GOrnergrat), on November 7/8th 1993, using the

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standard photometer. TIRGO is a 1.5 m cassegrain reflector with a wobbling secondary, sited at Gornergrat Nordturm (Gornergrat, Zermatt, Switzerland), at 3150 m altitude. The high altitude ensures that the precipitable water vapour content in the atmosphere above the telescope is very low, as are ambient temperatures at night, giving high sensitivity and excellent photometric stability. A monochannel photometer was used with an InSb detector cooled with pumped nitrogen. An integrating amplifier is used; before starting each measurement, the system reads the ramp and adjusts the signal sampling parameters automatically to optimize the measurement. The system has an ABBA chop cycle, with the chop frequency also being varied automatically according to the strength of the source ($\sim$ 10 Hz for a very strong source, down to $\sim$ 2 Hz for an extremely weak one). The chop amplitude was 70 arcseconds in Right Ascension. A 21 arcsecond diaphram was used in J and H and 14 arcseconds in K and L'. The bandpasses of the infrared filters are close to the "standard" infrared values.

The type GO V star HR660 was used as the primary photometric reference for 3C 66A, although a "basket" of stars were used for the overall calibration and calculation of the extinction. HR660 is 8° soutli of 3C 66A thus ensuring a good local photometric reference. Pairs of observations of this star were made before and after 3C 66A, as well as twice during the monitoring run. The magnitudes for HR660 were taken from the list of standard stars calibrated for the Carlos Sánchez Telescope (Kidger 1992) which are calibrated against the photometric zero point defined by Vega. The maximum range of airmass was 1.04–1.26 for HR660 and 1.00–1.13 for 3C 66A, thus all the observations were taken with the quasar close to the zenith. A nearby bright star was used as an off-set guide star. This ensures that the tracking during an integration was accurate to better that two arcseconds and that the rms tracking error was very much smaller.

The data acquisition program does not permit pseudo-simultaneous photometry to be taken (the measurement of a sequence of filters within a single integration cycle), so individual integrations were taken in each filter. Some 20 ABBA cycles were taken in J, whilst only 10 and 5 respectively were required to obtain a good s/n ratio (almost always > 50) in H and K. The total time taken to complete a JHK observation was in the range 18–25 minutes. Despite the much longer integration in J, due to the very much smaller signal in this band, the average signal to noise ratio was still a factor of 2 lower than in H or K. Observations were taken repeating the cycle JHK sequencially over nearly five hours, with occasional intervals to measure in L' and to measure HR660. Each ABBA cycle provided an individual estimation of the signal strength. To calculate the signal to noise for an integration, the mean and standard deviation of the individual cycles was calculated. The uncertainty in the mean signal is thus:

$$e_S = \frac{\sigma_S}{n^{0.5}} \quad (1)$$

where "n" is the number of ABBA cycles and "S" the mean signal. Thus the signal to noise is

Table 1. The light curve characteristics in the three filters presented in Fig. 1. The columns present sequentially the mean and standard deviation of the light curve, the number of points in the light curve and the probability that the observed variability is genuine

	Mean	σ	n	P(%)
J	12.304	0.023	10	72
H	11.553	0.030	11	98.5
K	10.881	0.048	14	99.99

$$s/n = \frac{S}{e_S} \quad (2)$$

which provides the photonic error for each integration. To obtain the true error on each point, a small term must be added in quadrature for the dispersion in the standard star measures. These values are found to be: J = 0.015 mags, H = 0.008 mags, K = 0.005 mags. The dispersion of the standard star magnitudes is found to be considerably smaller than the photonic error in the measures of the blazar.

3. Results

The light curve of 3C 66A is shown in Fig. 1. The gaps in the light curves at JD 98.35 and 98.45 are the points at which calibration observations were taken. Significant differences may be appreciated in the different bands. In J, there is no significant variation, with the magnitude virtually constant at J = 12.30. In H though, the light curve shows apparently smooth pseudo-sinusoidal variations of amplitude $\Delta H \sim 0.1$ mags, of a type that have been noted previously on a range of timescales in other objects and frequency ranges. Such variations appear to be essentially pseudo-periodic behaviour on occasions when they stabilise for several cycles. There is a slight tendency to a fade in the magnitude in H over the duration of the monitoring. The K light curve is rather noisier than that in H, but shows a persistent fade of approximately 0.13 mags. A particularly pronounced fade is seen at JD98.50, which appears to be reflected in the light curve in H, although the J light curve is completely non-variable at this time.

Analysis of the light curves in each filter using an F-test, to compare the dispersion and the errors in the data (Table 1), confirms their different variability characteristics:

Taking a minimum criterion for the reality of variability of 98%, the observed variation in H and K is, apparently, genuine, but is not significant in J. The fact that the three colours show different variability characteristics is inidicative that colour and thus spectral variations are taking place. As the observations in each band were not taken simultaneously, there is a possibility that false spectral variations may be induced by the no-simultaneity. Hence, a series of quasi-simultaneous spectra were produced by taking moving groups of three points (ie: the first spectrum was formed taking the first measurement in JHK, the second by taking H and K along with the first J of the next

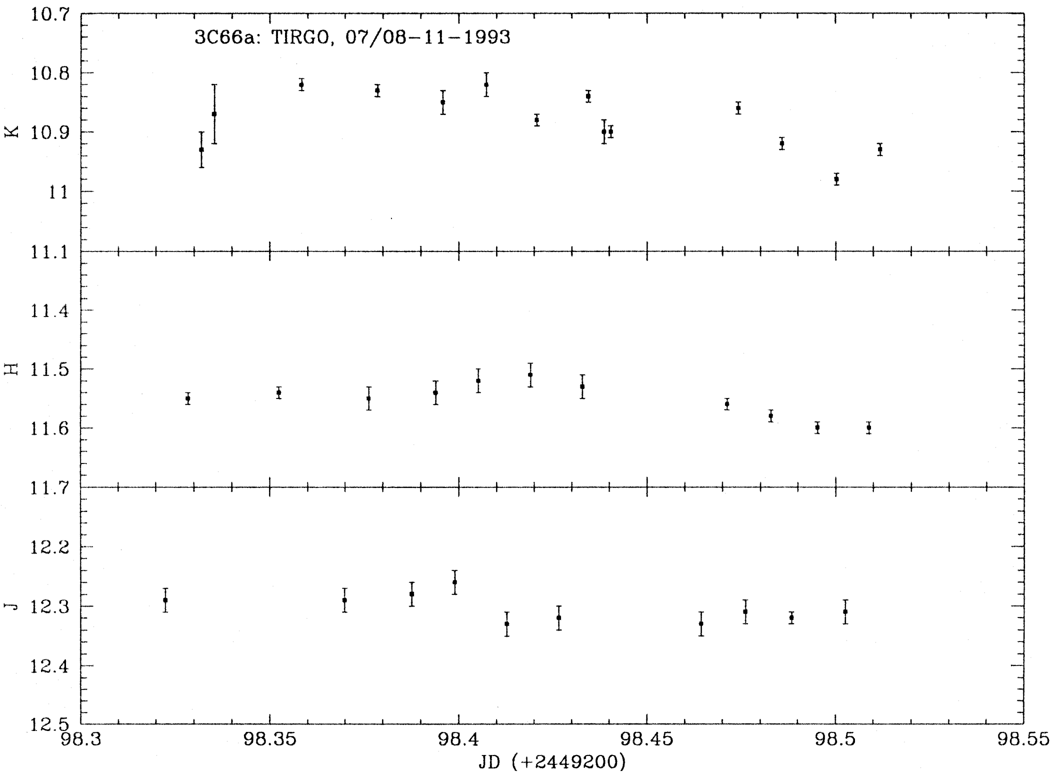


Fig. 1. The JHK light curves for tile observations reported in the text

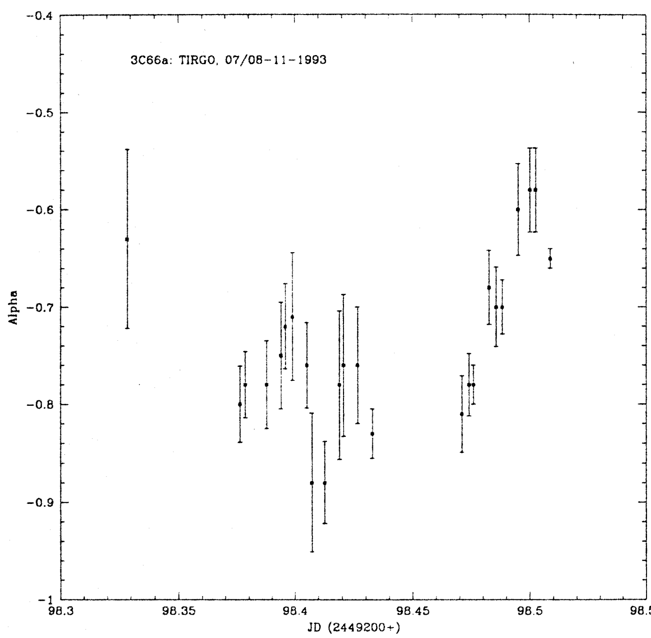


Fig. 2. Spectral index variations as a function of time, in the light curves presented in Fig. 1

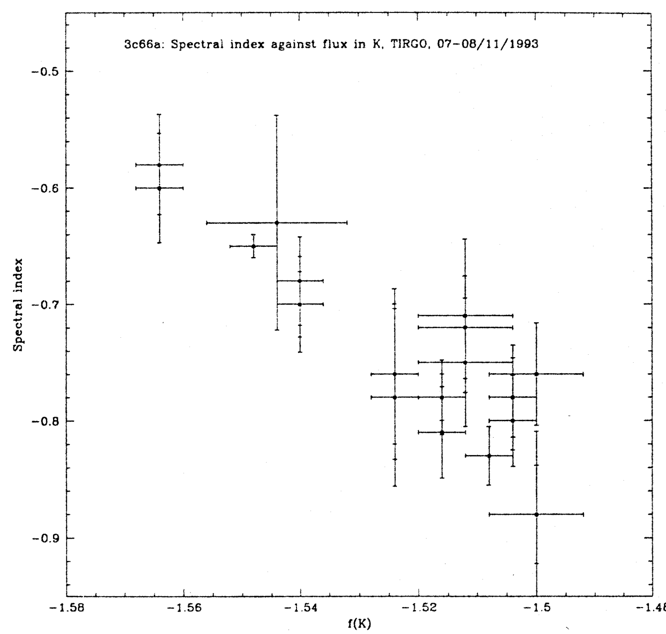
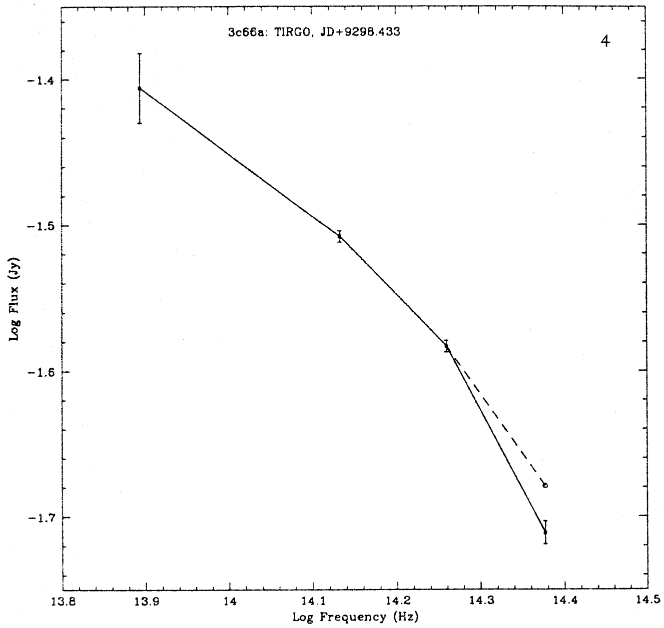
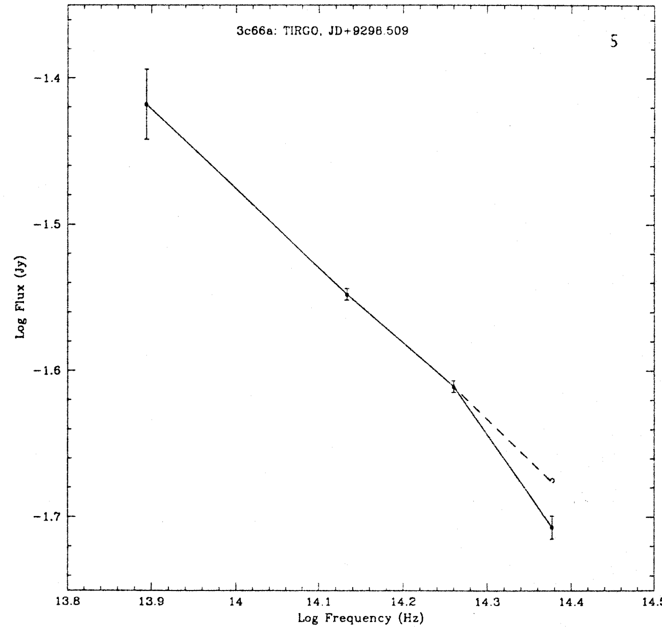


Fig. 3. Variation of spectral index against flux in K for the observations presented in the text

series, the next by taking the first K followed by J and H of the second series, etc.). Successive series JHK, HKJ, KJH, JHK,... are fitted individually by a least squares regression.

Figure 2 shows the variation of the spectral index during the observations. A maximum range from $\alpha = -0.88$ to $\alpha = -0.58$ is seen, significant at a level $> 99\%$. The spectral index flattens steadily from -0.81 to -0.58 in 40 minutes towards the end of the observations. Figure 3 shows the relation between the spectral index and the flux in K during the observations. A strong correlation is seen which has a significance $> 99\%$, although none is seen between the spectral index and the flux in either J or H. Such a correlation has been observed in the past





Figs. 4 and 5. Spectra of for the two epochs when observations were taken in HKL. The broken line represents the extrapolation to J if an empirically determined zero point correction of +8% is applied to the fluxes in this band

between the flux in J and spectral index (Gear et al. 1986; Kidger et al. 1994c. The sense of the charge (the continuum is bluer when fainter) is in the opposite sense to that generally observed in blazars. This correlation can be seen in Figs. 4 and 5 which show the continuum spectrum in $JHKL'$ at the two epochs when all four bands were observed. The second spectrum, with K at minimum, is a good power law, the first is strongly curved, far more so than can be explained by errors of calibration.

An adjustment of +8% in the fluxes in J of HR 660 makes Fig. 5 into an almost exact power law (broken line), as would be expected for a predominantly synchrotron source. This discrepancy seems to be due to a difference in the effective band in J between the photometry of the Carlos Sinchez Telescope (Kidger et al. 1992; Kidger 1992 and TIRGO (Hunt et al. 1986)) The standard star lists for the two telescopes show good agreement for common stars in H and K, but some discrepancies in J of as much as 10%, not closely correlated with the colour. The J. band is susceptible to unusual colour effects due to the convolution of detector response, atmospheric window and filter profile giving an effective ramp profile. Figure 4 though still shows the strongly curved spectrum even after the adjustment, suggesting that this was a genuine, if temporary feature.

4. Discussion

It is often assumed that the very fastest variability observed in blazars is due to processes in the accretion disk. Carrasco et al. (1985) explained rapid periodic variations in OJ287 as be due to "hot spots" on a thick accretion disk which is observed almost pole on (Sikora 1981). Relativistic beaming can occur in such a system (Blandford & Rees 1978) allowing super-Eddington luminosities. A number of variants on this model exist. Vila (1979) considers the possibility of pulsational modes in the accretion disk compatible with the pseudo-sinusoidal variability seen in our light curve in H and, on other occasions, in other blazars; e.g.: the quasi-periodicity observed in 4C 29.45 (Grauer 1984).

Abramovicz et al. (1992) suggest that accretion disk generated variability is caused by the generation and evolution of vortices. They point out that the X-ray variability spectra of AGNs is consistent (Abramovicz et al. 1989, 1991) with a model of many, well separated, bright hot spots on the surface of the disk. For non-zero viewing angle, spots at different radii will produce different characteristic amplitudes and periods of variation, giving an essentially chaotic result. These spots are regions of emerging flux tubes, energy will be emitted that has originated within the accretion disk and, if the spots appear as depressions in the surface of the disk, some behaving may occur in the throat of the spot.

It would be thus possible to generate most of the observed types of microvariability. If there are many spots, with no dominant site of activity, the variations provoked by individual spots would sum to give a low level of observed microvariability. If there are several dominant, or strongly beamed spots, their combined orbital periods can give rise to quasi-sinusoidal variations of the type that we observe in H. This explanation fits the strongly aperiodic nature of the variations better than a pulsational model, although the latter cannot be ruled out. A single dominant structure can give rise to strongly, or moderately strongly periodic behaviour. Whilst turbulence in the accretion disk will tend to form vortices or magnetic flux tubes (McWilliams 1990; Meacham et al. 1990), wave generation would have the opposite effect (McWilliams 1984; Maltrud & Vallis 1991), hence such vortices may be strongly temporal structures. Support for this view is provided by the highly ephemeral nature of many of the observed "periodicities".

Curved spectra in the optical/infrared region are uncommon, but have been observed on a number of occasions. In particular, Holmes et al. (1984) find that the infrared spectral index of OJ287 ($\alpha_{\rm IR} = -0.87$) is simlar to the value that we find for 3C 66A, even though the optical spectral index is considerably steeper ($\alpha_{\rm opt} = -1.25$). Similar curvature has been seen in the optical-ultraviolet in OJ287 (Maraschi et al. 1983) and in the blazar 1156+295 (Glassgold et al. 1983). In 1156+295 Glassgold et al. consider a synchrotron self-Compton model to explain the spectral curvature.

5. A possible model

If we have a short-lived thermal source superimposed on the synchrotron source that normally dominates the emission, various features of the light curve and spectrum can be easily understood. This model is qualitatively capable of explaining the spectral shape adequately if the temperature of the emitting source is $\sim$ 1500 K and the variation can be explained by cooling or occultation of the emitting source. There are though still quantitative problems in generating sufficient energy by thermal processes to explain the peak flux that is observed. If we have a black body emitting region of diameter "d", then the maximum output from the spot is:

$$9.35\,10^{-5} r^2 \,\mathrm{erg\,s^{-1}\,Hz^{-1}} \tag{3}$$

This is equated to the observed flux density in K of 3 $\sim$ 3 mJy, or $3\,10^{-26}\,\mathrm{erg\,s^{-1}\,cm^{-2}\,Hz^{-1}}$. If the distance to 3C 66A is "D", then the total output from the source is:

$$3\,10^{-26} \cdot 4\pi D^2 = 3.8\,10^{-25} D^2 \tag{4}$$

Hence:

$$9.35\,10^{-5} d^2 = 3.8\,10^{-25} D^2 \tag{5}$$

If $H_0 = 80$ and $q_0 = 0$, then $D \sim 1.4$ Gpc, or $D \sim 4\,10^{27}$ cm. Substituting into (3):

$$d \sim 3\,10^{17}\,\mathrm{cm} \tag{6}$$

Hence, the peak flux in K suggests that emitting region is close to 10^7 light seconds (approximately 4 light months) in diameter. However, the time scale of variability that we see is some three orders of magnitude faster. Thus, even black body radiation has real difficulties in explaining the observed variation qualitatively. Even if we allow for the presence of strong relativistic beaming in the spot, either because we see the rotation of the accretion disk at an angle (Carrasco et al. 1985), or because of acceleration in the throat of the magnetic flux tube (Abramovicz et al. 1992), the rapid time scale of the variation again seems to pose insuperable difficulties.

Both a synchrotron self-Compton model and a two-component (synchrotron + black body) model are capable of explaining some aspects of the change in the spectrum, but face serious difficulties of detail. Of the two, we favour the latter, if only because it seems less implausible and provides a simpler method of explaining the large change in spectral shape and strong excess at K. Even so, a second process must also be at work, either to boost the energy emission from the spot, or to modify the energy spectrum.

Assuming a thick accretion disk, one possibility for modification of the energy from the spot might be extinction. If the spot were deep in the throat of the accretion disk, close to the inner edge, it is possible that it might be seen through part of the disk itself. Given a low extinction at 2 microns and a much higher one at 1 micron, the spot might be observed clearly at longer wavelengths (K and L), but not in J. Total extinction, for example, to the centre of the Milky Way, decreases very rapidly in the infrared (Rieke and Lebofsky 1985), hence this process could be a plausible way of accounting for the observed spectral changes. If geometrical effects are invoked that cause very high extinction towards the hot spot or flare, the problem of the very rapid change in spectral shape and curvature could disappear.

If we have a 12 000 K, optically thin gas, emitting bremsstrahlung radiation, we could obtain a sharp frequency cut-off in the spectrum near the observed H band. For the gas to have an optical depth $\tau \leq 1$ and to produce the observed lumnosity would require a density $\rho \sim 2\,10^{10}$ particles cm^{-3} and $r \sim 2\,10^{16}$ cm. If we invoke extinction in the line of sight, we obtain the same result with higher temperatures, higher densities and smaller radii. As $r \propto t^{-1.1}$, increasing the gas temperature to 100 000 K would reduce the implied radius of emitting region to $r \sim 2\,10^{15}$ cm. Such a temperature would correspond to a major flare in the accretion disk and is not unreasonable. In fact, to produce X-ray flares, even higher temperatures may be implied; a 10^6 K flare would further reduce the size of the emitting region to approximately the radius implied by the observed variation time scale. Whilst we do not claim that there was a 10^6 K flare in the accretion disk, we cite it as one example of how the apparent contradiction could possibly be resolved.

6. Conclusions

Whilst our observations of microvariability in the infrared light curve of 3C 66A are qualitatively compatible with accretion disk models, important questions are raised by the data. In particular, the large difference between the J and K light curves implies very large spectral variations on very short time scales. We find significant variations in the spectral index in an interval of $\sim$ 40 minutes and a large change in spectral curvature in $\sim$ 2 hours. Whilst both spectral curvature and spectral index changes can be understood in terms of quite simple models (e.g.: synchrotron self-Compton, or an injection of relativistic electrons), the time scale of the changes that we observe is at least two orders of magnitude too fast to be accounted for in this way. Similarly, whilst a thermal flare provides a good fit to the observed change in the spectral shape, the implied diameter of the emitting region of the thermal energy is incompatible with the time scale of the variation. It is not obvious what the solution to this problem is.

Of the different possibilities, we favour an accretion-disk related origin for the variations, principally due to their very fast time scale and thus limited region in which they occour. Probably the source is a hot spot or flare on the disk, but a further process must be invoked too. Conceivably this process might be a high level of extinction in the line of sight to the spot, which masks the variation in J, whilst permitting variability to be observed in K. Such a model is possible if the accretion disk is thick and the spot occours deep in the throat, close to the inner edge.

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