Mon. Not. R. astr. Soc. (1971) **153**, 29–40.

OBSERVATIONS OF NGC 4151 DURING 1970 IN THE OPTICAL AND INFRA-RED

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(Received 1971 March 11)

SUMMARY

Observations of NGC 4151 at seven wavelengths from 0·3 to 3·4 microns made during the 1970 season are presented. Variations are found at all observed wavelengths but the optical and infra-red light curves are different: an optical maximum was reached in April but the galaxy continued brightening at 2·2μ until the end of June. The energy distributions of the point source and the background galaxy have been separated and that of the point source closely resembles that of the quasar 3C273. The general form of the light curves can possibly be attributed to a dust model for the infra-red emission but this would be ruled out if suspected rapid infra-red variations are confirmed.

INTRODUCTION

NGC 4151 is a Seyfert galaxy with a bright stellar nucleus. Optical observations by both photoelectric and photographic means show that this nucleus varies in the optical in a way reminiscent of quasars and N-type galaxies (Fitch, Pacholczyk & Weymann 1967; Barnes 1968; Pacholczyk & Weymann 1968a; Zaitseva & Ljutyj 1969; Cannon, Penston & Brett 1971). The galaxy was shown to have an infra-red excess by Pacholczyk & Weymann (1968b) and by Low & Kleinmann (1968). Observations at 10μ by Low & Kleinmann (1968), Kleinmann & Low (1970) and Stein & Gillett (1969) suggest variability with a time scale of one year.

In this paper we present optical and infra-red data on NGC 4151 during the 1970 observing season.

OPTICAL OBSERVATIONS

The optical observations of NGC 4151 have been made by two methods—photoelectric photometry performed on the 20-inch and 60-inch reflectors of the Hale Observatories at Mount Palomar and Mount Wilson respectively and photographic photometry on the 26-inch Thompson refractor at the Royal Greenwich Observatory.

The photoelectric observations were made in the *UBVr* system of Sandage & Smith (1963) with several focal-plane apertures with the results listed in Table I. The internal scatter present in multiple observations, combined with the uncertainty of the system deduced from observations of standard stars yields an r.m.s. error of the *V*, *B–V*, *U–B* and *V–r* observations of 0·05, 0·03, 0·06 and 0·04 mag respectively. Observations were made with several apertures to help detect centring errors which are easier to make with a nebulous object like NGC 4151 than with a star of comparable magnitude. The measurements with the smallest aperture were also generally repeated after independently centring the object.

TABLE I

UBVr observations of NGC 4151

Date 1970	J.D. 2440000+	Telescope Inches	Aperture diameter Seconds	Magnitudes *V*	 *B–V*	 *U–B*	*V–r*	Comments
Apr 1/2	678·8	20	25	11·73	+0·71	−0·33		
			48	11·40	+0·72	−0·24		
			78	11·14	+0·73	−0·19		
Apr 2/3	679·9	20	25	(12·33	+0·57	−0·26)		Obj. not centred?
			48	11·48	+0·77	−0·30		
			78	11·11	+0·79	−0·22		
Apr 29/30	706·8	20	25	11·41	+0·81	−0·36		Mean of 2
			48	11·14	+0·81	−0·31		
			78	10·87	+0·81	−0·30		
			124	10·64	+0·82	−0·22		
Apr 30/May 1	707·8	20	25	11·70	+0·73	−0·46		Mean of 2
			48	11·32	+0·72	−0·31		
			78	11·05	+0·74	−0·24		
May 8/9	715·7	60	8·1	12·12	+0·48	−0·57	+0·77	
			12·7	11·92	+0·56	−0·54	+0·83	
			20	11·66	+0·56	−0·47	(+0·67)	*V–r* prob. wrong
			29	11·57	+0·54	−0·43	(+1·16)	*V–r* prob. wrong
			44	11·34	+0·67	−0·31	+0·76	
June 1/2	739·7	20	25	11·67	+0·74	−0·16	+0·79	Mean of 2
			48	11·37	+0·77	−0·19	+0·78	
			78	11·13	+0·76	−0·12	+0·73	
July 1/2	769·7	20	25	11·76	+0·80	−0·37		Mean of 2
			48	11·42	+0·83	−0·18		
			78	11·08	+0·88	−0·21		
			124	10·92	+0·74	−0·06		
July 5/6	772·7	60	8·1	12·26	+0·62	−0·55	+0·83	
			12·7	12·06	+0·66	−0·38	+0·86	
July 29/30	798·7	20	25	11·76	+0·76	−0·36		Mean of 2
			48	11·56	+0·72	−0·23		
			78	11·36	+0·63	−0·29		
July 30/31	799·7	20	25	11·62	+0·86	−0·33		Mean of 2
			48	11·41	+0·80	−0·36		

The photographic observations listed in Table II were taken on Kodak IIaO plates which, in combination with the absorption present in the refractor give a good approximation to the *B* system. The plates, mostly taken out of focus, were reduced against a photoelectric sequence based on one kindly supplied by Dr T. D. Kinman. The errors involved in photographic photometry of galaxies were discussed in detail by Cannon *et al.* (1971); for NGC 4151 the scatter of observations on a single night indicates the r.m.s. error of a single plate is 0·07 mag.

TABLE II

Photographic observations of NGC 4151

Date 1970	J.D. 2440000+	Magnitudes B	No. of Plates
Feb 10/11	628·6	13·24	1
Mar 3/4	649·6	12·89	1
Mar 6/7	652·6	12·82	2
Apr 6/7	683·6	12·59	4
Apr 8/9	685·5	12·53	4
Apr 27/28	704·5	12·60	4
May 2/3	709·4	12·56	2
May 3/4	710·4	12·55	2
May 8/9	715·5	12·60	2
May 23/24	730·5	12·88	2
May 27/28	734·5	12·81	1
May 28/29	735·5	12·88	2
May 29/30	736·5	12·78	1
June 1/2	739·5	12·91	1

In Fig. 1, the light curves in six colours are given. The results in the blue from both photoelectric and photographic methods are plotted together; since there is a difference of zero-point between the two sets of observations, the photographic observations have been arbitrarily plotted 0·3 mag brighter to bring them into better agreement with the photoelectric results. The adjustment is necessitated by the smaller effective aperture of the photographic image compared with the 25″ diameter aperture of the photoelectric results.

The light curves in the blue and the ultra-violet show a rapid rise from February to a maximum in April, then a slight decline to a fairly steady level lasting until the end of July. Since both sets of data are subject to potentially serious systematic errors, but of quite different natures, it is reassuring that they agree so well. The night-to-night variations of 0·1 mag are probably real and have been reported by other observers. The visual light curve shows little variation. As found by other workers, the pattern of variation appears clearer in the blue than in the visual and is clearest in the ultra-violet; it should be noted that the total variation in 1970 has a smaller amplitude than in the past.

INFRA-RED OBSERVATIONS

The infra-red observations have been made at 1·6, 2·2 and 3·4μ at the 200-inch telescope on Mount Palomar, the 100-inch and 60-inch telescopes on Mount Wilson and the 36-inch and 84-inch telescopes of the Kitt Peak National Observatory. The photometers used are similar to that described by Becklin & Neugebauer (1968); the data were reduced using Johnson's magnitude system (Johnson *et al.* 1966). In most cases, observations have been made with several apertures to help guard against centring errors. Observations at the 200-inch show that the maximum of the infra-red emission is co-incident to within at least one second of arc with the optical nucleus.

The infra-red data are presented in Table III and Figs 1 and 3. In Fig. 1 the photometry within either 15″ or 10″ apertures are shown as a function of time; for several dates it was necessary to interpolate the data from that of adjoining apertures.

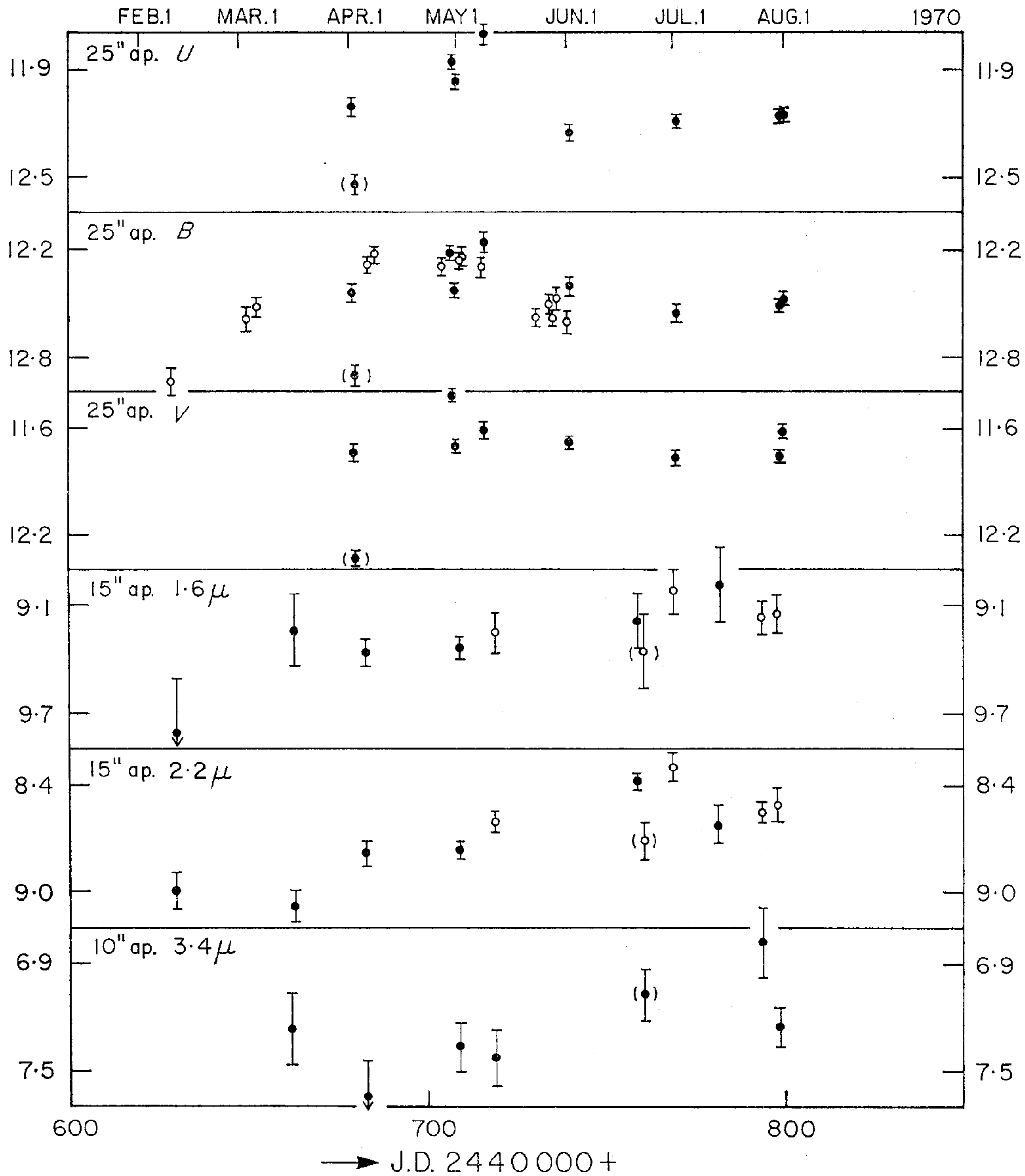

FIG. 1. *Light curves of NGC* 4151. *In the B curve open circles represent photographic observations from which* 0·3 *mag has been arbitrarily subtracted to take into account differences of system and aperture. In the* 1·6 *and* 2·2μ *curves open circles denote observations with* 10" *apertures corrected by the subtraction of* 0·3 *and* 0·15 *mag respectively. Those in parenthesis are probably doubtful because of centring errors; e.g. on April* 2/3 *the observations with the larger apertures agree with the previous nights observations.*

Variability in excess of 2 standard deviations is observed during the observing period of 100 days. The standard deviations in the derived magnitudes of a nearby reference star during the nights when NGC 4151 was observed were 0·03, 0·05 and 0·08 at 1·6, 2·2, and 3·4μ respectively. The variability in NGC 4151 is made more plausible by the presentation in Fig. 3 which shows that during late June the flux changed consistently in all apertures although the largest change is observed in the smallest apertures.

TABLE III

Infra-red observations of NGC 4151

Date	J.D.	Telescope	Aperture diameter		Magnitudes		Comment
1968	2439000+	Inches	Seconds	1·6μ	2·2μ	3·4μ	
Mar 10/11	927	200	5·0		8·61 ± 0·10		
1970	2440000+						
Feb 12/13	630	60	15·4	9·81 ± 0·31	8·99 ± 0·11		
Mar 17/18/19	663	36	16·5	9·23 ± 0·20	9·07 ± 0·09	7·26 ± 0·22	Mean of 2 nights
			33	8·75 ± 0·28	8·50 ± 0·07		
Apr 6/7	683	100	7·5	9·70 ± 0·12	8·93 ± 0·12	7·75 ± 0·25	
			9·6	9·66 ± 0·08	8·95 ± 0·08	7·63 ± 0·20	
			15·0	9·36 ± 0·08	8·78 ± 0·08	7·83 ± 0·42	
			20	9·19 ± 0·08	8·70 ± 0·08		
Apr 20/21/22	697	60	32	8·74 ± 0·15	8·30 ± 0·08		Mean of 2 nights
May 2/3	709	100	9·6	9·61 ± 0·08	8·91 ± 0·05	7·36 ± 0·14	
			20	9·05 ± 0·06	8·59 ± 0·05		
May 12/13	719	84	5·3	9·54 ± 0·17	8·99 ± 0·12	7·51 ± 0·22	
			10·1	9·55 ± 0·12	8·75 ± 0·06	7·42 ± 0·16	

TABLE III (*continued*)

Infra-red observations of NGC 4151

Date 1968	J.D. 2439000+	Telescope Inches	Aperture diameter Seconds	Magnitudes 1·6μ	2·2μ	3·4μ	Comment
June 21/22/23	759	60	7·9	9·10±0·18	8·42±0·05		Mean of 2 nights
			15·3	9·18±0·16	8·38±0·05		
			23	8·72±0·12	8·15±0·09		
June 23/24	761	84	10·1	9·65±0·21	8·86±0·11	7·07±0·15	See text
July 1/2	769	100	9·6	9·22±0·13	8·45±0·08		
			13·6	9·13±0·08	8·41±0·08		
			20	8·83±0·10	8·19±0·08		
July 14/15/16	782	60	7·9	9·58±0·46	9·00±0·12		Mean of 2 nights
			10·6	9·96±0·32	8·88±0·22		
			15·4	8·98±0·21	8·62±0·11		
			32	8·91±0·16	8·22±0·09		
			40	8·78±0·17	8·26±0·09		
July 26/27	794	200	4·9	9·96±0·10	8·97±0·10	7·12±0·12	
			9·8	9·46±0·06	8·70±0·06	6·78±0·20	
			12·7	9·35±0·10	8·64±0·08		
July 30/31	798	200	3·3	10·02±0·12	9·03±0·12	7·64±0·15	
			6·9	9·60±0·11	8·77±0·11	7·30±0·15	
			9·8	9·44±0·11	8·66±0·10	7·25±0·11	

There is a suggestion that the 1·6μ brightness reaches a maximum at the same epoch as the 2·2μ brightness; it is clear, however, that the optical and infra-red magnitudes do not vary together. While in the optical the maximum was reached in April, the object continued brightening at 2·2μ until the end of June—an interval of about 70 days. The 3·4μ data are not good enough to draw an unambiguous light curve.

There is some evidence in the data for the possibility of rapid variations in the infra-red which, if present, would be very important in distinguishing between different mechanism of infra-red emission (Rees *et al.* 1969). A possible example of rapid variation exists in the 3·4μ observations of July 26/27 and July 30/31. Observations were made with two apertures on both dates which indicate changes in the same sense: this argues against the possibility of centring errors. As pointed out above, combining the data from different apertures makes the change more significant than appears from the size of the error bars in Fig. 1. On the other hand there is no change at 2·2μ between the same epochs.

There is also an indication of rapid variations at 2·2μ between June 21/22/23 (the mean of June 21/22 and June 22/23) and June 23/24. However, the later, fainter observation was made with only one aperture and was at a large airmass; therefore the possibility of a centring error cannot be excluded. Thus, variations on a time scale of the order of a week in the infra-red cannot be ruled out and confirming observations are needed.

DISCUSSION

In Figs 2 and 3 the observations are plotted at different dates as a function of the diameter of the observing aperture. It is seen that when the object is brighter the slope of the magnitude–aperture relation is flatter in a way that is consistent with a variable point-source in the centre of the object plus an unvarying component of finite dimensions. The curves are steepest in the visual and steeper in the blue than the ultra-violet corresponding to the greater contribution of the central source in the blue colours. Additionally the variation from night-to-night is greater in the bluer colours and in the central region.

An attempt has been made to separate the point-source from the underlying galaxy by making a least-squares fit to a simple model using the data in all colours, at all epochs, and with all apertures. It was assumed that the galaxy itself does not vary, has the colours of M31 (Sandage, Becklin & Neugebauer 1969), and has a radial distribution of light such that the flux within an aperture of diameter D is proportional to D^{α}. The exponent α as well as the magnitudes in each colour of the point-source at each date of observation and the brightness of the galaxy were then determined.

This procedure is detailed in the Appendix; is not the same as that of Pacholczyk & Wisniewski (1967), who did not solve for the brightness of the galaxy which they subtracted in their study of NGC 1068.

The simple model outlined above gives a reasonable statistical fit to the data; the chi-square for 103 degrees of freedom is equal to 175. In Fig. 4 the energy distribution for the galaxy and that found for the point-source in early May are plotted; the energy distribution of the latter has great similarity to that of the quasar 3C273.

The ratio of the optical to 2·2μ intensities of the point-source found by the fitting procedure varies by a factor of 4 between early April and late June. However,

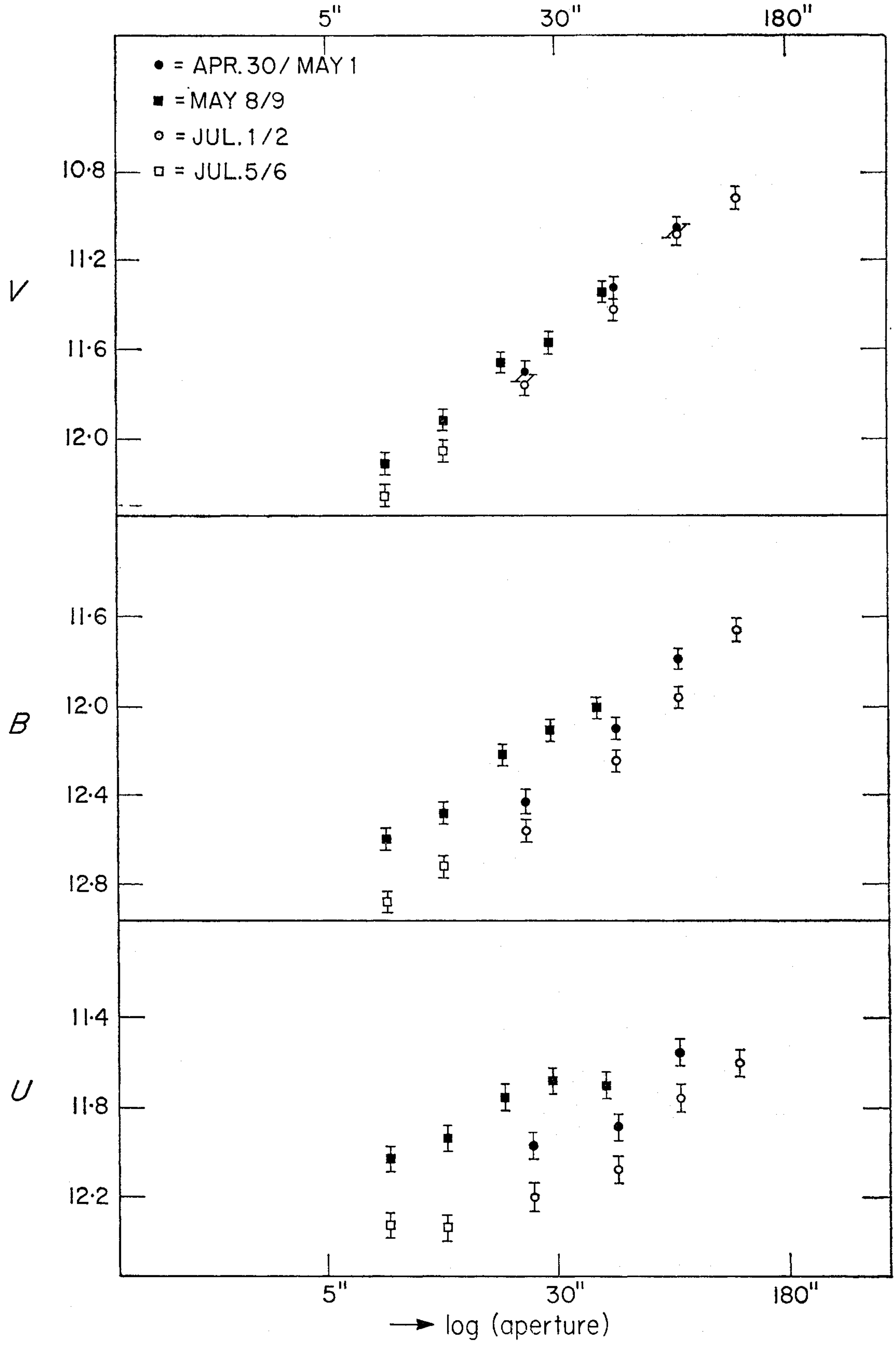

FIG. 2. *UBV magnitudes plotted against diameter of aperture for NGC* 4151. *Closed circles denote measurements on* 1970 *April* 30/*May* 1, *closed squares May* 8/9, *open circles July* 1/2 *and open squares July* 5/6.

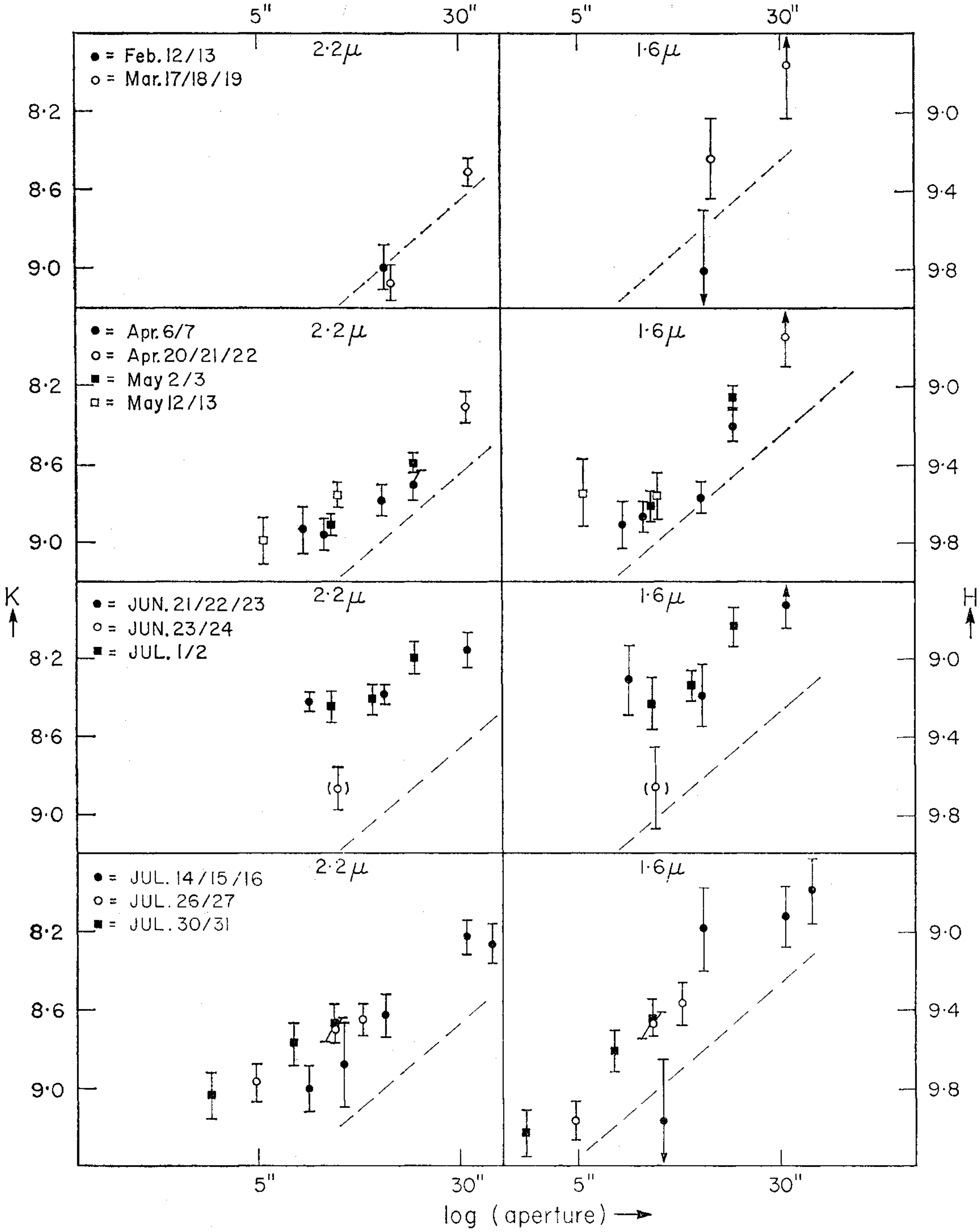

FIG. 3. 1·6μ *and* 2·2μ *magnitudes plotted against diameter of aperture for NGC* 4151. *The observations are grouped into four different sets by epoch. The dashed lines, which have approximately the same slope as that of the relationship between V and diameter, are plotted in the same position in each diagram to guide the eye.*

the purely optical colours $U–B$, $B–V$, $V–r$ or the infra-red colour $K(2{\cdot}2\mu)-L(3{\cdot}4\mu)$ do not vary significantly. This independent variation suggests to us that the sources of optical and infra-red emission are also independent.

The observed time lag between the maxima in the infra-red and the optical can possibly be attributed to the light travel time from a central source to a dust shell surrounding that source. For a shell which has its peak emission near 3·4μ this

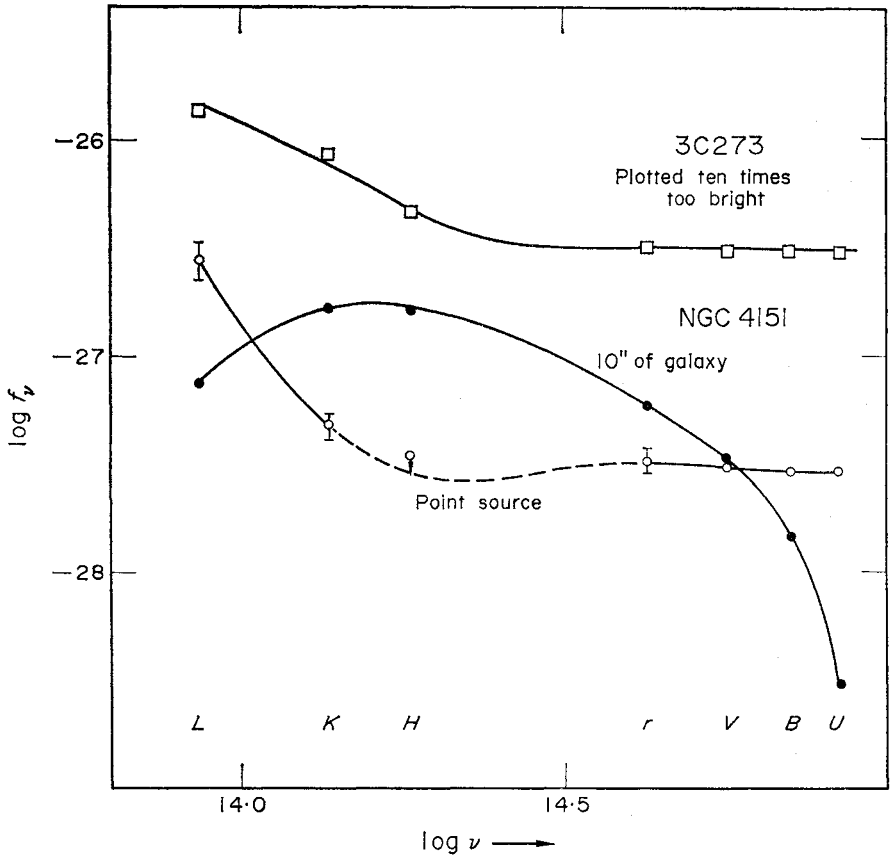

FIG. 4. *The energy distribution deduced from our model for the point source at the nucleus of NGC* 4151 *from the optical observations of* 1970 *April* 29/30, *April* 30/*May* 1 *and May* 8/9 *and the infra-red observations of* 1970 *May* 2/3 *is plotted together with that deduced from the background galaxy within a* 10" *diameter aperture. For comparison the energy distribution of the quasar* 3C273 *from the UBVR observations of Johnson* (1964) *and infra-red magnitudes measured by one of* (*G. N.*) *on* 1970 *July* 30/31 *is also plotted.*

delay time must be at least a month since dust closer than about 3×10^{17} cm to a source emitting 10^{43} erg s^{-1} would have a temperature $T > \sim 600$ °K and would evaporate. However, Rees *et al.* (1969) have pointed out that if the infra-red emission is due to dust one cannot expect variations at a wavelength of λ microns much more rapidly than τ, where

$$\tau = \left(\frac{\lambda}{2{\cdot}2}\right)^{5/2} L_{44}{}^{1/2} \text{ months}$$

and L_{44} is the infra-red luminosity in units of 10^{44} erg s^{-1}. Adopting $L_{44} \sim 0{\cdot}1$ for NGC 4151 we see a dust model forbids variations faster than about a month at $3{\cdot}4\mu$. Thus if the rapid variations with a time scale of about a week are confirmed this model of radiation by dust would be excluded. Of course it is by no means certain that the optical and infra-red light curves bear any causal relationship to each other at all. We note that in sources which are variable at radio wavelengths and where the emission mechanism is presumably due to synchrotron radiation the variations occur first at short wavelengths and move with time towards longer wavelengths. Thus dust may not be the only way this effect may be explained.

More observations of the type we have made are plainly needed to establish the reality of the rapid variations and to see if the delay in the infra-red light curve is repeated in another event.

ACKNOWLEDGMENTS

We are grateful to our night assistants Gene Hancock, Eugene Marosan, Pete Mastrosimone, Gary Tuton, and Tom Zinter and our colleagues John Danziger, Gordon Garmire, Frank Porter and Henry Tye for help in obtaining the infra-red observations. Mrs Rosemary Selmes measured most of the photographic material described here.

We are also grateful to Dr T. D. Kinman for supplying us with a photoelectric sequence for NGC 4151 in advance of publication.

One of us (M. V. P.) acknowledges the support of a Carnegie Fellowship, another of us (M. J. P.) wishes to thank the Carnegie Institution of Washington for providing hospitality and the status of Guest Investigator during the period of this work. Two of us (E. E. B. and N. V.) were Visiting Astronomers at the Kitt Peak National Observatory, which is operated by the Association of Universities for Research in Astronomy Inc., under contract with the National Science Foundation. This work was also supported in part by NASA Grant NGL 05-002-007. We are all grateful to the observatories at which we have worked for a generous allocation of observing time.

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APPENDIX

This appendix gives details of the method of separating the point source at the nucleus of NGC 4151 from the light from the rest of the galaxy. There are observations on dates $i = 1, \ldots I$ in colours $j = 1, \ldots J$ through apertures with diameters $D_k = D_1, \ldots D_K$ seconds of arc showing that the flux from the source is Φ_{ijk}. This flux is the sum of that from the point source at that day and colour, f_{ij}, and that from the rest of the galaxy in that colour through that size aperture, $c_j F(D_k)$. Here c_j represents the colour of the galaxy and the function F describes the spatial distribution of flux from the galaxy assumed to be the same in all colours, i.e.

$$\Phi_{ijk} = f_{ij} + c_j F(D_k).$$

A simple two-parameter family of functions was picked to represent F:

$$F(D) = F_{10}\left(\frac{D}{10}\right)^{\alpha}$$

where $F_{10} = F(10'')$ and the colours c_j were imposed to be the same as those of M31 (Sandage *et al.* 1969). Then a least-squares solution for f_{ij}, F_{10}, and α was performed by minimizing $S = \Sigma\, \omega_{ijk}(\Phi_{ijk} - f_{ij} - c_j F_{10}(D_k/10)^{\alpha})^2$ where ω_{ijk} is a weight deduced from the observational error of Φ_{ijk}. Since S is not linear in α, trial solutions were made for different values of α to find which value gave a minimum in S. This procedure gave $\alpha = 0{\cdot}6 \pm 0{\cdot}05$. The solution for the other parameters f_{ij} and F_{10} is then straightforward. The normal equations are:

$$\sum_{\substack{\text{all } k \\ \text{each } i,\, j}} \omega_{ijk}\left(\Phi_{ijk} - f_{ij} - c_j F_{10}\left(\frac{D_k}{10}\right)^{\alpha}\right) = 0$$

and

$$\sum \omega_{ijk} c_j \left(\frac{D_k}{10}\right)^{\alpha}\left(\Phi_{ijk} - f_{ij} - c_j F_{10}\left(\frac{D_k}{10}\right)^{\alpha}\right) = 0$$

which may be easily solved by elimination.

In the case discussed in this paper, the solution was for 67 unknowns from 170 observations and the goodness of the fit may be judged from the value of

$$\chi^2 = \frac{S}{m} = 175$$

where $m = 103$ is the number of degrees of freedom in the solution. Given the fact that the colours were imposed, and the limitation on the form of $F(D)$, this seems reasonable.

Fig. 4 shows the result of the above solution using the computed F_{10}, the flux from the galaxy in a ten second aperture, and f_{ij}, the flux from the point source using the data from early May. The calibration from magnitudes to flux was given by Becklin (1968).