CCD PHOTOMETRY OF 6 NEAR-EARTH ASTEROIDS

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Abstract. Photometric observations of 11 near-Earth asteroids were made within a regular NEA CCD photometric programme at Ondřejov Observatory in the first half of 1994. This paper shows obtained R lightcurves, V-R, R-I, and B-V color indices, and rotation preriods for 6 of them. Among the presented results, the most interesting are those for (4954) Eric, for which we obtained several high-quality lightcurves and which seems to indicate a surface heterogeneity, (1864) Daedalus, for which interesting comparison with older observations by Gehrels *et al.* (1971) can be made, and 1993 VW, for which the unusual color characteristics were observed. Two (1994 AW_1 and 1994 GY) of the other three observed objects have fast rotations with periods of about 2.5 hours and relatively low amplitudes. Subsequent analysis of additional lightcurve data for 1994 AW_1 has revealed a presence of two periods in its lightcurve (Pravec *et al.* 1995). The last object presented here is 1994 JF_1, for which only lower limits on period and amplitude were determined.

1. Introduction

Photometric investigation of asteroids can reveal important physical parameters of the bodies, namely, rotation periods, surface characteristics (both color and roughness), overall shapes and spin vectors. While the observing and interpreting methods are rather well understood for the case of main-belt asteroids (e.g. Magnusson 1986, Magnusson *et al.* 1989, Magnusson 1992, Binzel *et al.* 1993), the situation is different in the case of near-earth asteroids (NEAs).

Main difficulty of photometric observations of NEAs is in the fact, that they are small and observable only at not too large distances from the Earth. This fact has two basic consequences:

- Low frequency of occurence of favorable observing conditions for most of NEAs. Favorable apparitions have usually short duration (often only

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a few weeks or months) and they occur usually only once per many years.

- Limited range of ecliptic longitudes, in which a particular NEA is accessible photometrically. It generally limits a possibility to eliminate some of the ambiguities in lightcurve interpretations.

Observations of NEAs are further complicated by the fact, that they usually have fast apparent motion and low brigthness. Also ephemerides available for them are often not so accurate, as for the case of MBAs. This is due to generally lower number of available positional observations in past and several times smaller distances from the Earth, when compared with MBAs.

We have begun a regular NEA photometric programme at the Ondřejov Observatory in January 1994. This project is based on collaboration between the Astronomical Institutes of the Czech Academy of Sciences and the Charles University Prague, and supported in part by a grant within the ESO C&EE Programme (see Pravec and Wolf 1994). Its objective is to obtain sufficient number of lightcurves for as many observable NEAs as possible and to determine their periods and color characteristics. We try to photometrize all newly discovered NEAs brighter than V=17.5, because a discovery apparition is usually the most favorable one for many years. Also known NEAs in good observing conditions are observed. The aim of this observing strategy is to enlarge a sample of NEAs' rotation periods and surface characteristics and to provide baseline lightcurve data for further investigations.

2. Observations and data reductions

The CCD photometric observations of selected NEAs were carried out during the period from January to June 1994. The SBIG ST-6 CCD camera located in the primary focus of the 65cm reflecting telescope at the Ondřejov Observatory was used. The CCD exposures were made primarily through the standard R filter, with supplement measurements through the V, I, and B filters at intervals. Precise aperture photometry was performed on image series using an photometric software by Velen and Pravec. For more details on the camera and photometric software see Pravec *et al.* (1994).

Nightly differential lightcurves were produced with respect to an ensemble of selected local comparison stars to eliminate random errors and possible variability of individual stars. Usually at least five comparison stars were measured together with an asteroid. On best nights the measurements were calibrated using the Landolt (1992) standard stars.

We observed 11 NEAs during the first half year of our regular observing program. Here we present the first results for 6 of them. See Table I for an observing log for the presented lightcurves. Errors (in the 5th column)

TABLE I
Observational circumstances

Minor planet	UT 1994	Dist. Earth AU	Dist. Sun AU	Phase deg.	Error mag	Shift in c.l. mag	Mag. scale
(1864) Daedalus	Mar 5.1	1.024	1.893	19.7	0.05	11.740	rel.
	Apr 5.9	0.686	1.682	5.6	0.015-0.03	0.000	cal.
	Apr 8.0	0.674	1.666	7.4	0.025-0.03	13.370	rel.
	Apr 28.9	0.626	1.500	30.1	0.05-0.1	14.210	rel.
(4954) Eric	Feb 14.1	0.798	1.745	13.6	0.004-0.006	12.040	rel.
	Feb 15.1	0.800	1.751	12.9	0.005-0.007	13.310	rel.
	Feb 17.0	0.805	1.763	11.7	0.010	0.000	cal.
	Mar 4.9	0.882	1.858	8.3	0.007	12.275	rel.
	Mar 10.9	0.929	1.892	10.6	0.007-0.01	12.830	rel.
	Mar 17.9	0.994	1.926	13.9	0.008	11.255	rel.
1993 VW	Jun 7.9	0.434	1.437	11.3	0.06	-	cal.
	Jun 12.9	0.479	1.473	14.4	0.06	-	cal.
1994 AW_1	Jan 14.8	0.191	1.172	8.9	0.013-0.033	11.650	rel.
	Jan 19.9	0.205	1.175	19.3	0.02	0.000	cal.
1994 GY	Apr 19.9	0.266	1.267	8.1	0.02	0.000	cal.
	Apr 21.0	0.264	1.265	8.2	0.03	14.408	rel.
	May 3.9	0.255	1.253	14.8	0.025	13.740	rel.
1994 JF_1	Jun 8.9	0.377	1.352	23.0	0.05	-	rel.

represent the ranges of error variations, or the medians of errors in some cases.

3. Results and Discussion

We successfully derived synodic periods for 4 of the 6 observed NEAs. We used a Fourier analysis method (see, e.g., Harris *et al.* 1989) for (4954) Eric and 1994 AW_1. The string-length minimization method (Dworetsky 1983) was used for period determination for (1864) Daedalus and 1994 GY. The composite R lightcurves for the four objects were constructed and they are presented in Figures 1, 2, 5 and 6. (The magnitude shifts of individual nightly lightcurves are given in Table I.) In Table II there are collected the derived synodic rotation periods, amplitudes and V-R color indices. Results for individual objects are discussed in next paragraphs. All times in the

TABLE II
Synodic periods, amplitudes and V-R color indices for presented NEAs

Minor planet	Period hour	Amplitude	V-R	Remark
(1864) Daedalus	8.572 ± 0.002	0.88-1.04	0.48 ± 0.03	
(4954) Eric	12.056 ± 0.002	0.66	0.50 ± 0.02	
1993 VW	-	-	0.24 ± 0.09	const. brightness?
1994 AW_1	2.52 ± 0.10	0.15	0.42 ± 0.03	see text
1994 GY	2.5553 ± 0.0017	0.06	0.41 ± 0.03	
1994 JF_1	> 9	≥0.30	-	lower limits

figures are corrected for the light travel time. The magnitudes are reduced to unit (1 AU) geocentric and heliocentric distances, but not for the phase effect. The solar phase angles are given in parentheses.

Results for individual objects

1. **(1864) Daedalus** was observed during four nights in March and April 1994. We derived a synodic period of (8.572±0.002)h. The R composite lightcurve is presented in Fig 1. It has a nearly symmetric shape. Although the brightness levels in maxima may not be exactly the same, since the vertical shift of the Apr 28.9 lightcurve points with respect to the Apr 5.1 lightcurve is somewhat uncertain, the first minimum is deeper by about 0.12 mag than the second one. There was a significant change of amplitude between April 5-6 and April 28; from 0.88 to 1.04. The change may be attributed to a change of the solar phase from 5.6 to 30.1 degrees between the two nights.

The asteroid was observed by Gehrels *et al.* (1971) on April 20 and 21, 1971. They obtained not complete lightcurve (one minimum missing) and were able to derive a period of $8^h34^m \pm 1^m = (8.567 \pm 0.017)$h. This is in agreement with our result. On April 21, 1971, they observed an amplitude of about 0.82 mag at phase angle of 22.8 deg (wrong value for the phase angle is given in the original paper by Gehrels *et al.*). We compared their 1971 lightcurve with the R composite lightcurve presented in Fig. 1 and found, that the minimum observed by Gehrels *et al.* is probably the secondary minimum, for which we found an amplitude of 0.76 at phase angle of 7.4 deg. Since the observing geometric conditions (ecliptic longitudes and aspect angles) were similar in April 1971 and April 1994, the difference between the amplitudes of the secondary minimum observed in 1971 and 1994 may be attributed again to the dependence on the solar phase angle

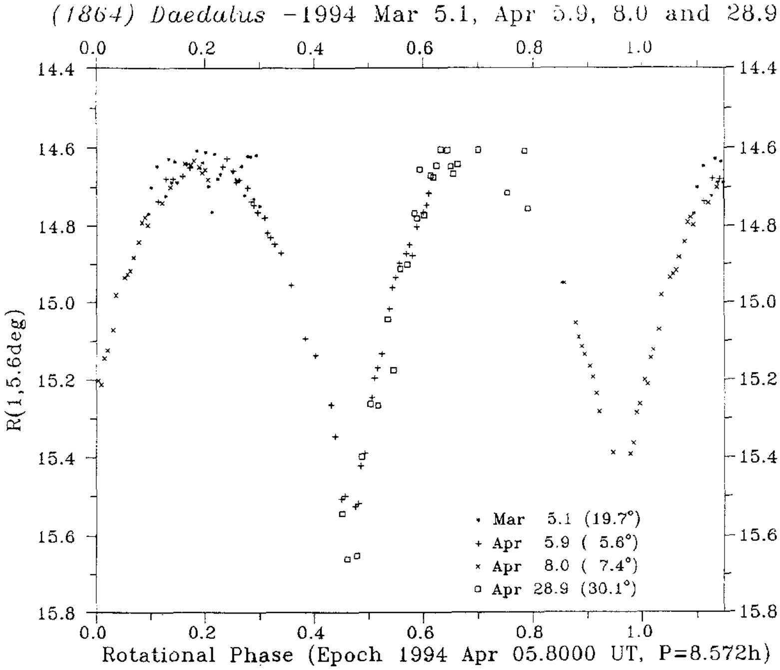

Fig. 1. Composite lightcurve of (1864) Daedalus, constructed from four nightly lightcurves obtained between 1994 Mar 5.1 and Apr 28.9. The R magnitudes were reduced to unit geocentric and heliocentric distances and for phase angle of 5.6°. The period of 8.572±0.002 hr was detected.

(see previous paragraph). The amplitude-phase dependence may be approximated by a linear function with a slope of (0.006±0.002) mag/deg for the primary minimum.

The asteroid was observable again in December 1994 and January 1995, reaching magnitude V=17.4, when important lightcurve data could be obtained on different aspect. Also completion of the calibration of the 1994 March and April data should bring another information about the phase dependences for this object.

2. **(4954) Eric**, one of larger (in order of 8 km) Amor-type objects, is the best observed NEA during the first half year of our observing project. The synodic period of (12.056±0.002)h was derived from data obtained during six nights between February 14 and March 17, 1994. The composite R lightcurve constructed from the six nights is presented in Fig. 2. The nearly 1:2 commensurability of the synodic period to the Earth rotation period makes it virtually impossible to cover the whole rotation cycle during one night observing session from one station. The data spanned over more than

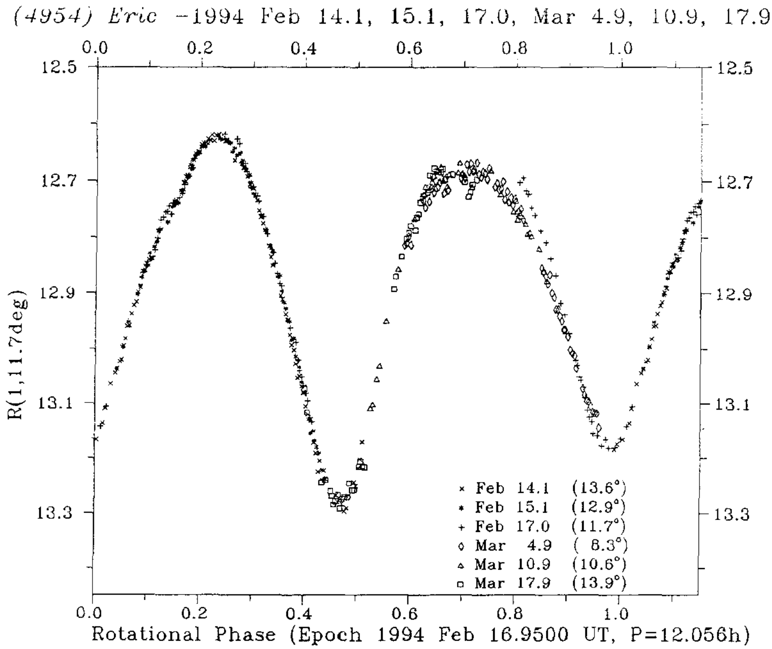

Fig. 2. Composite lightcurve of (4954) Eric, constructed from six nightly lightcurves obtained between 1994 Feb 14.1 and Mar 17.9. The R magnitudes were reduced to unit geocentric and heliocentric distances and for phase angle of 11.7°. The period of 12.056±0.002 hr was detected.

one month were needed to be put together to construct the complete composite lightcurve.

There are a few interesting points about (4954) Eric. The first one regards the shape of the lightcurve. While the portion covering the higher maximum and deeper minimum (phases from 0 to 0.6 in Fig. 2) is fairly smooth and the minimum has virtually the same shape in both the February 13-17 data and the March 17 data subsets, the rest of the lightcurve has more irregular shape. There is a rapid brigthness variation in the secondary maximum (around phase 0.7) on the scale of a few tens of minutes, with the range of variation of several hundreth of magnitude (i.e. more than three times the standard error of one point). The patterns of the variation are different on different nights. The second peculiarity of the composite lightcurve is on the decreasing branch between 0.8 and 1.0. There is a significant non-correspondence between the shape of this branch in the Feb 17.0 lightcurve and those ones from March 4.9 and 10.9, 1994. This may correspond to a real change of the lightcurve shape due to the change of solar phase, namely the "sign" of the solar phase between the non-consisnent observations, as the asteroid passed opposition on February 28, 1994.

Another interesting point about (4954) Eric is an indication of color variations correlated with rotational phase, firstly noted by Y. Krugly *et al.* (1994, *personal communication*) from their UBV photometry. Our preliminary analysis of our B, V, and I data taken around 1994 Feb 17.0 indicates, that there is a variation of B-V and R-I, but not of V-R. However, this result is only preliminary and must be confirmed after careful recalibration of all of our color measurement data. Around 1994 Feb 17.0 the mean V-R, R-I and B-V indices were 0.50, 0.37, 0.87, with errors 0.02, 0.02 and 0.03, respectively.

There is an extensive unpublished dataset for (4954) Eric obtained by Krugly *et al.* (1994, *personal comm.*) in August, September and November 1993, and February and March 1994. We also have to reduce another two nights from April 27 and 29, 1994, which will be useful primarily for the solar phase curve establishing. Next apparitions with moderately favorable conditions will occur around May 1995 (maximal brightness 16.7 in V, observable from the southern hemisphere), March 1997 (15.3, both hemispheres) and June 1998 (16.5, southern hemisphere). Modeling and further observing effort will bring new interesting results for this object.

3. **1993 VW** was observed on 2 nights in June 1994. The R lightcurves are presented in Figures 3 and 4. The accuracy was rather low; the standard deviation σ of individual points in the lightcurves is about 0.06 magnitude. The 1-σ error bars are also plotted in the figures. The observations are consistent with the hypothesis of constant brightness of the asteroid on both nights. Any possible variation on a scale of several hours should have amplitude lower than 0.1 magnitude. Also the mean magnitudes on both nights may fairly well correspond to the same cross-section, since the difference between them might be explained by a change of solar phase. Clearly, we can say nothing conclusive about the rotational period of 1993 VW using the available lightcurve data. Both the low amplitude and long period hypotheses are plausible.

This asteroid has an unusual blue color. The color indices are V-R=0.24 ± 0.09 and R-I=0.26 ± 0.05. According to Binzel and Bus (1994), the asteroid's spectral properties over 0.4-1.0 μm resemble the Q-type asteroid (1862) Apollo and possibly ordinary chondrite meteorites. Unfortunately, 1993 VW will not be observable again in favorable conditions before year 2000.

4. **1994 AW$_1$** was discovered on January 11, 1994 (see MPEC 1994-A06 and B02). We observed it around January 14.8 and 19.9. The limited amount of available data causes an ambiguity of determined rotation period. We have derived a set of possible periods. This set is formed by the first 9 members of an arithmetical progression in frequencies. The first member is 1/(2.627h), the last member is 1/(2.419h), and the difference is 0.00409/h;

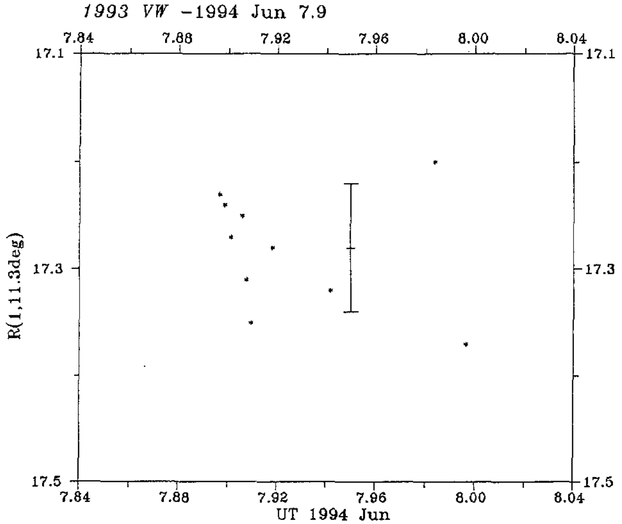

Fig. 3. R lightcurve of 1993 VW obtained around 1994 Jun 7.9, reduced to unit geocentric and heliocentric distances. $1-\sigma$ error bar is also shown.

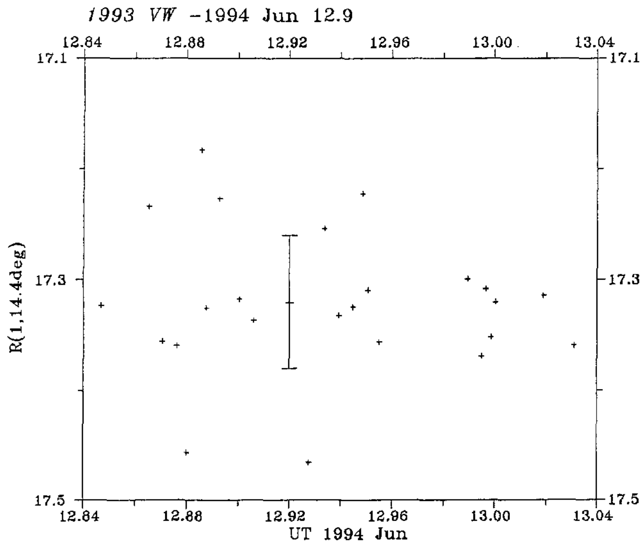

Fig. 4. R lightcurve of 1993 VW obtained around 1994 Jun 12.9, reduced to unit geocentric and heliocentric distances. $1-\sigma$ error bar is also shown.

error of each possible period is 0.002h. This character of the ambiguity is caused by the availability of data only from the two non-consecutive nights. The median of the set and the most probable period is (2.519±0.002)h, but its probability is insignificantly higher than the other ones among the set of

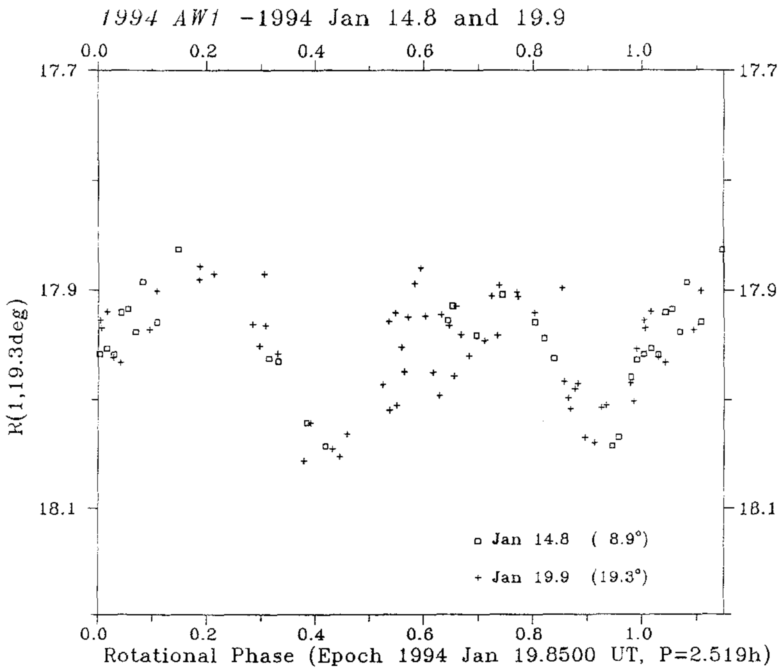

Fig. 5. Composite lightcurve of 1994 AW_1, constructed from two nightly lightcurves obtained around 1994 Jan 14.8 and 19.9. The R magnitudes were reduced to unit geocentric and heliocentric distances and for phase angle of 19.3°. The period of 2.519 hr is a median from the set of 9 possible periods.

9 periods. So we conclude, that the period is (2.52±0.10)h. The composite R lightcurve for the most probable period is presented in Fig. 5.

Another extensive dataset was obtained by Mottola *et al.* (1995). They obtained 8 lightcurves between 1994 Feb 8 and 19. The analysis of the full dataset of 10 available lightcurves (2 from this paper and 8 from Mottola *et al.*) shows a presence of two periods in the lightcurve of 1994 AW_1 (see Pravec *et al.* 1995). The period of 2.52 hours derived here from the 1994 January data only is the shorter of the two periods.

5. **1994 GY** was discovered on April 14, 1994 (see MPEC 1994-H01 and H05). We observed it on two nights in April and one night in May 1994. We derived a synodic period of (2.5553±0.0017)h. The composite lightcurve is presented in Fig. 6. It has rather low amplitude of about 0.06 mag. There is an indication of different brightness levels of the two maxima, so the derived period probably corresponds to the true rotation period. Nevertheless, the other possibility of lightcurve with one maximum cannot be completely ruled out.

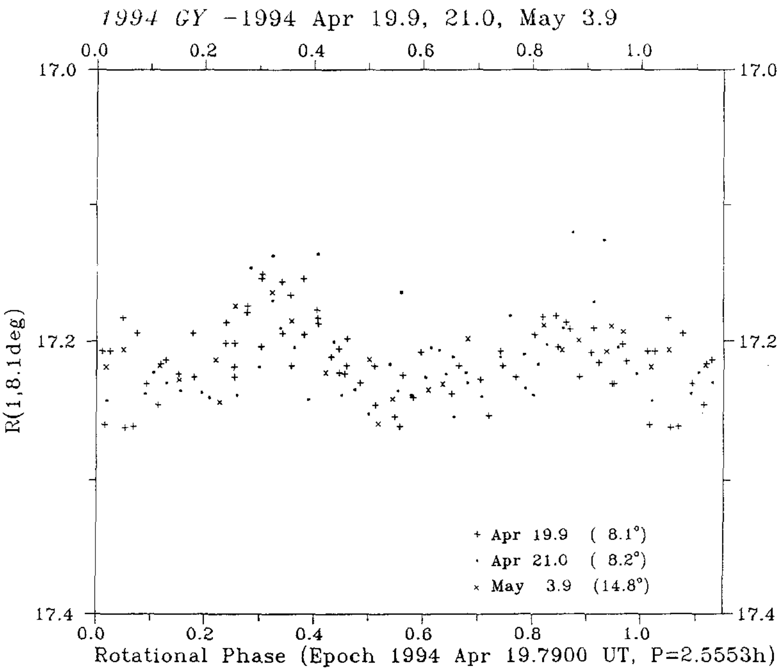

Fig. 6. Composite lightcurve of 1994 GY, constructed from three nightly lightcurves obtained between 1994 Apr 19.9 and May 3.9. The R magnitudes were reduced to unit geocentric and heliocentric distances and for phase angle of 8.1°. The period of (2.5553 ± 0.0017) hr was detected.

The color indices are V-R=0.41, R-I=0.38, and B-V=0.76, with errors 0.03, 0.03, and 0.06 mag.

6. **1994 JF$_1$** was observed on June 8, 1994. The R lightcurve is presented in Figure 7. We obtained conservative lower limits on amplitude (0.30) and period (9 hours, assuming regular double maximum lightcurve). No data through other filters were obtained. This asteroid will be observable again in April and May 1998, reaching magnitude of 17.7.

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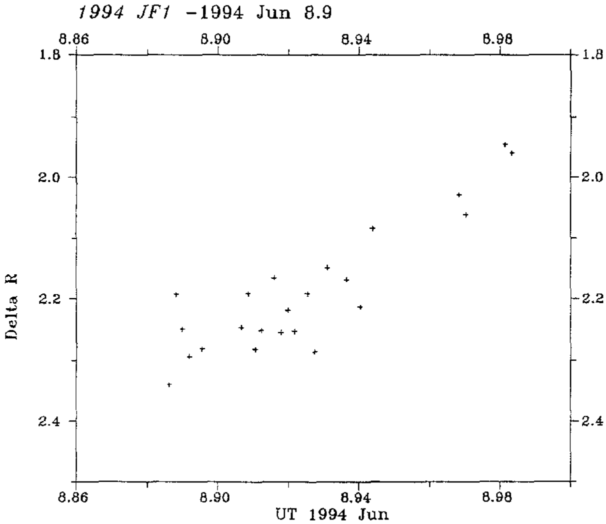

Fig. 7. Relative R lightcurve of 1994 JF_1 obtained around 1994 Jun 8.9, reduced to unit geocentric and heliocentric distances.

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