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# A simple automatic photoelectric telescope

## Part I: Overview and results

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**A telescope has been built, which will, after being set up on a group of stars, automatically cycle between them, taking photometric readings. This introductory paper gives an overview, describing the system in general terms, the sequence of system development and the results achieved so far.**

**Arising from this, Parts II and III will give a detailed description of the system, concentrating on hardware and software respectively.**

### Introduction

In 1982, the authors became interested in photoelectric photometry (PEP)[1] and built a manually operated system with computer data logging.[2] The system worked successfully and, between 1984 September and 1988 March, there were 160 observing sessions, performing differential photometry to determine times of minima of eclipsing binary stars.

With this system, despite the computer assistance, the observer is still required to move the telescope to each star or sky position, centre each star in the pinhole, manipulate the photometer head, and press some buttons. This work by the observer, not difficult in itself, has to be done every forty seconds, between each reading. Since observing runs last for a period of at least three hours, this work becomes tiring. This system has never been used after 2 a.m. local time, solely because the observer needs to sleep. Many hours of dark clear skies have thus been missed.

In 1986 December, therefore, we decided to build an automatic photoelectric telescope.

### Automatic photoelectric telescopes

An automatic photoelectric telescope (APT) is a computer controlled telescope, designed specifically for the purpose of conducting photoelectric photometry without human intervention. A typical APT is a small, short focal-length instrument, on an equatorial fork mounting. The photometer head is permanently mounted at the eyepiece. Telescope movement is controlled by stepper motors which, for each step, turn the telescope by a known amount about each axis; it thus works using an essentially 'open loop' control system. Such a telescope cannot, in practice, operate successfully for more than about half an hour, because the telescope would gradually drift out of alignment with the target stars. The key idea behind successful APTs is occasionally to 'close the loop', by using the photometer to detect the presence of, and to centre, the stars in the pinhole.

Such telescopes have been in existence for a number of years in the USA,[3,4] where amateur astronomers have played a prominent role in their development. Of particular note are the state-of-the-art instruments developed by Hall, Boyd and Genet[5] (a professional astronomer and two amateurs). This consortium has set up an 'APT service' whereby professional astronomers and organisations may buy time on their telescopes. Their telescopes, situated in isolated mountain-top locations, are able to work automatically for several months at a time, performing whole-sky photometry of variable stars. Such systems are highly sophisticated; for instance, they require automatic weather-sensors and shut-down procedures.

An earlier and, by comparison, simple design of APT is that of David Skillman.[6] His system requires a short set-up by the observer at the beginning of each evening's observing session, and performs differential, rather than whole-sky, photometry. Some authorities describe such systems as Skillman's as 'semi-automatic'. We prefer the term 'simple automatic', not least because the system allows the observer more than a semi-night's sleep!

### General requirements

Our wish was for an APT with which to continue our programme of observing eclipsing binary stars. Since this APT was to be located in a suburban back garden, rather than at an isolated site, complete automation would be of little benefit; furthermore, whole-sky photometry is not practicable in England. These factors motivated our decision to build an APT similar in functionality to that of Skillman, although our solution, giving greater emphasis to software, contrasts with Mr Skillman's, which makes use of his skills in electronics.

There were further requirements we wished our APT to satisfy. First, the telescope had to be able to continue working – locating and centring stars – under imperfect sky conditions. There are several reasons for this. The software controlling the APT is complex, and the time needed to test it would be greatly extended if this could only be done under perfect skies. Further, with differential photometry, the accuracy of any given magnitude determination depends only upon the accuracy of

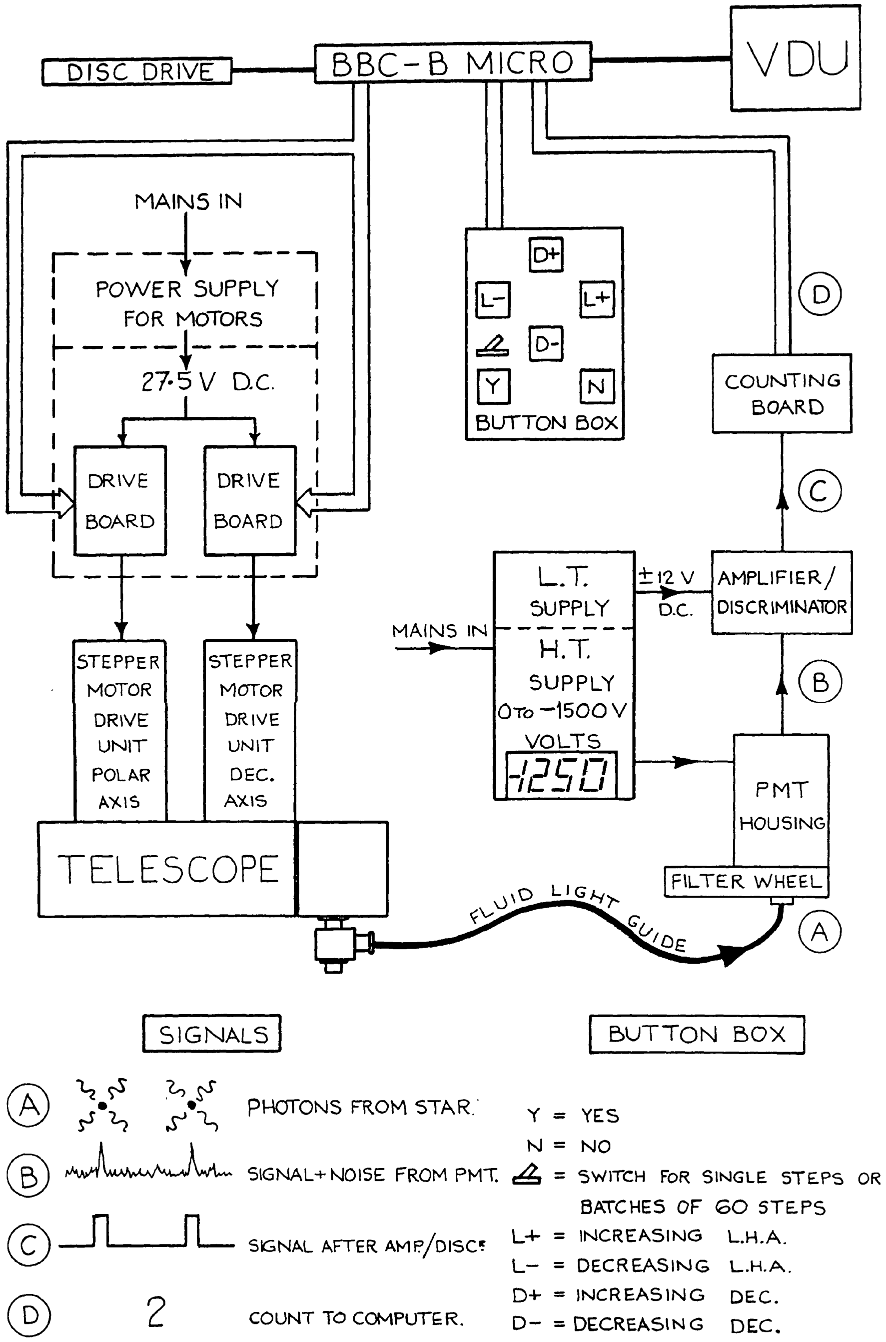

**Figure 1.** Schematic diagram showing the major components of the APT system.

the readings in the bracket[1] upon which it is based. Accuracy therefore depends upon having clear skies for a period of about five minutes. So, if the APT is robust enough to be able to continue working while a cloud is passing, then good results, which would otherwise be lost, will be obtained after the cloud has gone.

Second, we wanted the system to be flexible, with no computer-imposed constraints. In particular, we wanted the ability to select different observing sequences, according to the target to be observed. We also wanted the ability to choose comparison and check stars during set-up, rather than in advance. In building this flexibility into the system, we found that, as a bonus, our APT would be able to follow moving targets, such as asteroids. This facility is discussed in Part III.

Finally, to encourage maximum usage, we wished the observer set-up and shut-down to be as quick and easy as possible. Achieving this requirement depends upon careful design of both mechanics and software.

**Figure 2.** A general view showing the APT being set up for use. J. E. is standing by the telescope. Once set-up is complete, the doors of the run-off shed would be closed, protecting the trolley containing the electronics.

## Our APT

Figure 1 shows a schematic view of our system. We decided to use the JEAP photometer,[7] as it is ideally suited to our application. This photometer head (PMH) is especially convenient for small telescopes, as only a small and lightweight part – essentially a mirror-box, with eyepiece, graticule and pinholes – is attached to the eyepiece tube of the telescope. The bulk of the photometer head, containing an EMI 9924 end-window photomultiplier tube and a filter wheel, is housed away from the telescope. The two portions of the PMH are joined by a 3-m long fluid light guide. The photon-counting electronics for the JEAP were supplied by Norman Walker and John Watson. The figure shows schematically the stages by which photons arriving at the telescope give rise to a count at the computer. (In practice, large counts, from a few thousand to hundreds of thousands, are observed.) The figure also shows the circuitry used to control the stepper motors, and the button-box used during set-up.

Figure 2 shows our APT. The telescope is a 212-mm diameter f/4.0 Newtonian reflector. Its short, centrally pivoted, tube minimises deflections due to wind loading. The telescope has to be weather-resistant and rain tolerant. Even without rain it becomes totally saturated with dew during late autumn nights. The telescope has now been subjected many times to soakings and icy conditions, without problems.

There is only one stepper motor per axis. There is no separate tracking motor; tracking is controlled by software. The stepper motors each control their axis via a friction-wheel reduction train whose constancy of rate depends only on the circularity and centring of the discs and shafts. Making discs round and centering them to a high standard is much easier than achieving the same constancy using gears, worms or belt drives.

The electrical equipment is kept indoors when not in use, in order to protect it. When the telescope is set up, this equipment is carried to the telescope on a specially designed trolley which weighs 43 kg loaded. There are only four connections to be made, so set-up is quick, and there is little risk of damaging equipment.

The telescope is housed in a small roll-off shed; when the telescope is in use, the trolley is inside this shed, with the doors closed. The approximately 90-watts of heat generated by the electrics for the stepper motors keep the interior of the shed dry.

It is desirable that the observer is in a comfortable position during set-up. During this operation the stars need to be centred reasonably accurately on a graticule. A rotating head for the telescope tube permits the eyepiece to be in a horizontal position, no matter what part of the sky is being observed. To assist in locating the required field, there are large-diameter setting circles. There is also a star-chart holder, attached to the telescope tube, adjacent to the eyepiece. The chart is conveniently positioned and may easily be turned to any required orientation.

There is no computer shut-down procedure. Instead, operation is terminated by a time-switch, which cuts off power to the computer and other electrics.

## Site conditions and accuracies

Since the object of PEP is to measure the faint light emissions from distant objects, it might be supposed that a dark observing site is essential. In fact, the results that can be obtained in a light-polluted environment are only marginally less accurate, provided one does not attempt faint objects. Because of light pollution, we are restricted to observing stars of magnitude 10 or brighter. In a dark site, we estimate that our APT would be able to do useful work down to magnitude 11.

The APT is sited in typical suburban conditions. There are two busy roads nearby, and many street lamps within 150 metres; it is thus fortunate that buildings obstruct the horizon in most directions. The nearest unshielded street lamp is only 20 metres away from the telescope, at an elevation of 15 degrees; in addition, two nearby neighbours have installed 'security' lighting.

In spite of this, because the pollution is a constant, good results can be obtained. On a good night, i.e. one with no mist, no Moon and working above 45 degrees altitude, accuracies of 0.01 mag are often obtained.

Occasionally, for periods sometimes exceeding 4 hours, accuracies of 0.005 mag are obtained. A more average quality night will give an accuracy of 0.015 mag, but even a poor night, with accuracies as low as 0.03 mag, can still yield useful timings for our observing programme.

It is pertinent to state what is meant by the term 'accuracy' in this context. Generally, the cycle of stars comprises the variable, a comparison and a check star, each of which is measured with the same frequency. These are close together in the sky, so all suffer similar extinction due to air-mass. The check-star data are processed in exactly the same way as those of the variable,[1] giving a – hopefully constant – light-curve for the check star. The accuracies quoted above are the standard deviations of the check-star magnitudes. That measure of accuracy is conservative because any variability, in either the check or comparison star, will serve to inflate the figure. In performing this calculation, it is essential that there is no preliminary smoothing of the data.

We have expounded at length on this topic in the hope that others will not be discouraged from trying PEP, just because they have poor light-polluted sites.

## Costs

The total cost incurred for this system, including telescope, optics, JEAP items, foundation, run-off shed, microcomputer, disk drive and monitor, was approximately £2300. The last three items were bought second-hand at a cost of £200. Also, a number of machined items for the telescope and mounting were obtained at a very favourable price. On the other hand, the APT could have been built for less. By using a smaller mirror of, say, 15 cm diameter, a cheaper photometric system, and (painted) mild steel instead of aluminium alloy, one might save up to £700.

Regarding running costs, each data disk will accommodate 15 observations of 12 hours' duration, and each observation will need approximately 20 sheets of paper to hold all the information: about £1 per week will cover these items.

It can be seen that this is not a cheap system for the amateur, especially as it is of limited use in other applications. We feel, however, that it is an excellent investment, as it produces results of scientific value, and has much work to do, both now and in the foreseeable future.

## Diary of events

Unless all components function correctly, an APT will not work; in view of the uncertainties and the expenditure involved, construction was carried out in stages, testing at each stage before proceeding. These stages were:

Stage 1. Construct the telescope complete with both stepper-motor drives. Build stepper-motor drive circuits. Test exhaustively, to ensure that the stepper motor and gearless drives would be sufficiently accurate for PEP.

Stage 2. Build the foundation and run-off shed for housing the telescope. Order the JEAP and photon-counting electronics.

Stage 3. Purchase microcomputer, disk drive and monitor. (Prior testing had been done with our existing computer equipment.) Build trolley.

A more detailed diary of events follows:

1986

December. Decision to proceed with design of an APT.

1987

March. During the Winchester Weekend we visited Ron Arbour's photographic observatory and, as a result, decided to use a gearless friction drive.
April. Mechanical general arrangement and detail drawings of telescope complete.
May. Order for mirrors placed with AE Optics of Cambridge.
June. Most machined items received and ready for final drilling, tapping and assembly; additional materials purchased for tube; began work on software.
August. Two gearless drives ready; power supply unit for stepper motors built complete with interface to BBC microcomputer; mirrors received from AE Optics.
September. Telescope and mounting assembled indoors for prolonged testing of accuracy of stepper motor drives.
November. Tests satisfactorily completed; decision to purchase the JEAP PEP equipment and associated electronics.
December. Designing foundation and run-off shed.

1988

January. Foundation and shed complete; telescope erected on site.
February. Alignment of polar axis and tracking tests; also tests of cycling between a number of stars.
March. Visit to John Watson and Norman Walker, to bench-test and take delivery of JEAP and associated equipment.
April. Initial trials and first successful run of APT.

## Current work

The telescope is now regularly and reliably producing results of good quality: between 1988 April 20 and 1989 January 13, 85 runs have been made, of which 57 were useful, and 23 of little or no use; about the same ratio as for our manual equipment. A small number of observations has been made at the request of a professional astronomer, who wanted magnitude data for two suspected zeta Aurigae type eclipsing binary stars.

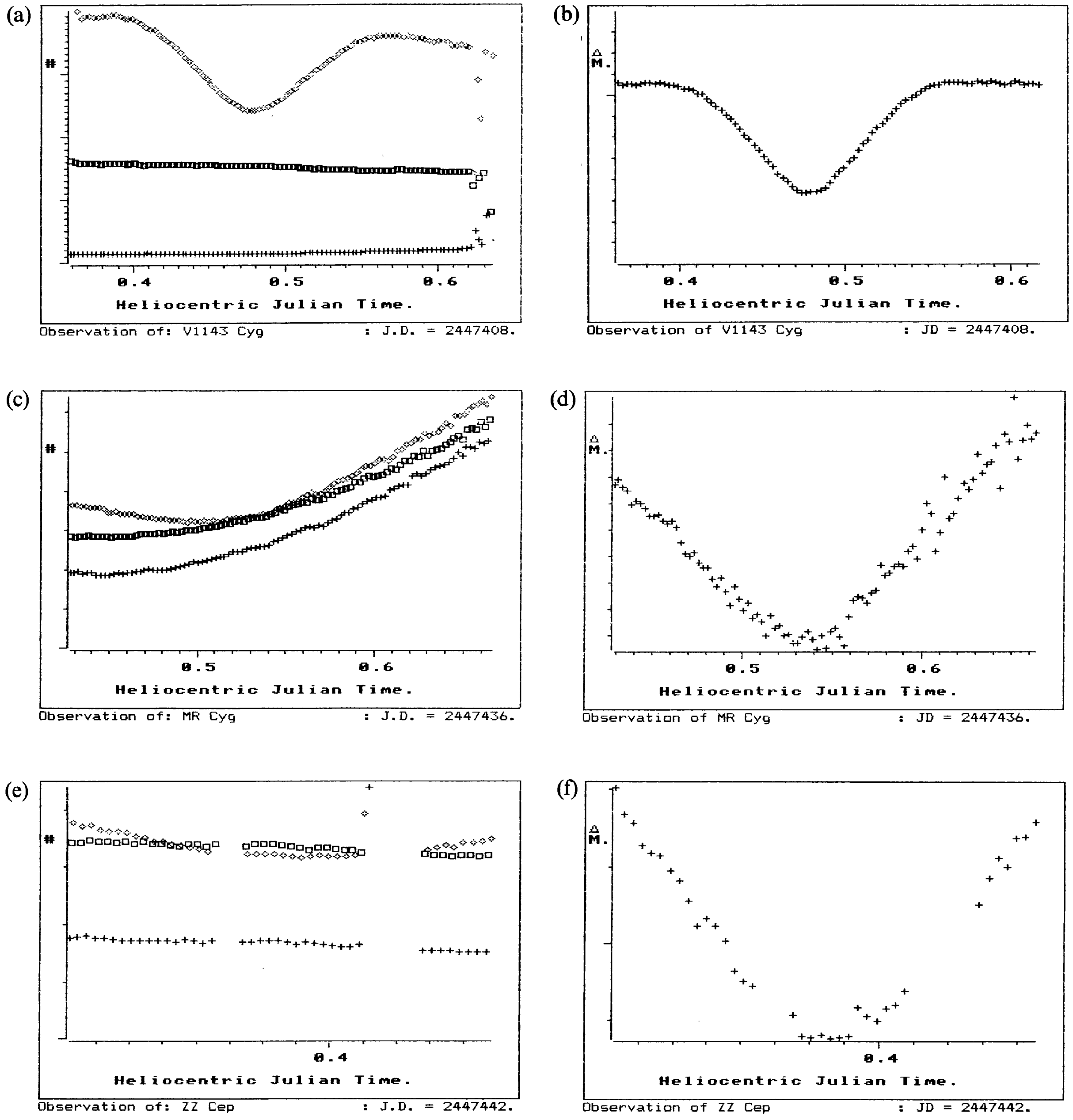

**Figure 3.** Sample results. Figure 3a shows plots of counts observed for V1143 Cygni on JD 2447408, and Figure 3b shows the resulting light-curve. Similarly, Figures 3c and 3d show an observation of MR Cygni made on JD 2447436; and Figures 3e and 3f show an observation of ZZ Cephei made on JD 2447442.

The major work remaining – planned for 1989 – is the fitting of an additional stepper motor to drive the filter wheel, which will allow UBV photometry to be performed, and also allow dark current readings to be taken. The main computer program will have to be modified slightly to allow for this, and the data reduction programs will have to be greatly altered.

## Comparison of systems

As the APT has now emerged from its initial testing period, it is worthwhile to compare it with our manual system.[2] The telescopes are situated four metres apart, so both are under the same poor skies. The APT uses photon counting with an end-window PMT, whereas the manual system is DC,[2] with a side-window tube. Despite the better photometer system of the APT, the observed accuracies are about the same, but under darker skies the APT photometer would probably perform better than the other, especially for faint stars.

The APT is able to take twice the number of readings per hour as the (already fast) manual system. The APT is also used, in practice, more than twice as often as the manual system, because it may be left unattended to work until dawn. These factors mean that the APT is four times as effective as the manual system.

In winter, the APT may often be used to make two observing runs per night, one starting at 6 p.m., and the other at midnight. The APT has also increased our ability to observe long eclipses: an eclipse of GT Cephei has been observed in a single 11.5-hour observing run. This would not have been attempted with our manual system.

## Sample results

The first photometric trial was made on 1988 April 6 and, as might be expected, there were several problems to be overcome: a further five runs were needed to do this. Finally, on 1988 April 20, a good observation, of the eclipsing binary VW Cephei, was obtained. This observation lasted for 4.8 hours and 75 magnitude determinations were made, which enabled both primary and secondary minima to be obtained. The timing of this successful run was fortuitous, since it enabled us to exhibit some reasonable results (rather than hopes and aspirations) at the professional/amateur meeting[8,9] of 1988 May 7.

Figure 3 shows three results, all observations of Algol-type eclipsing binary star systems, made with a V filter. The $x$-axis in each diagram is heliocentric Julian time (HJT), i.e. the fractional part of the full Julian date, corrected for light-travel time to the Sun.[1] In Figures 3a, c, e the $y$-axis is the count observed, in photons per second, marked by 10 000 (long ticks), and by 1000 (short ticks). The three curves plotted in these figures are the object (diamond), the comparison star (square), and the sky (cross). Figures 3b, d, f show the corresponding light-curves. The $y$-axis is delta-magnitude, i.e. the difference in magnitude between the object and the comparison star. This axis is marked by magnitudes (long ticks), and by tenths (short ticks). Because only a single filter is used, all magnitudes are differential instrumental magnitudes.

Figures 3a and 3b show a primary minimum for V1143 Cygni, which has a period of 7.64 days. This observation, made on JD 2447408, lasted 6.2 hours and it will be seen, from Figure 3a, that the sky readings were very well behaved until HJT 0.625, when a dramatic changed occurred. Up to this time, the standard deviation of the check star readings was less than 0.005 mag; thereafter, the sky counts more than doubled, and the stars counts were reduced. This type of behaviour has been seen many times on our manual system, and we may infer that this change was due to the presence of cloud. Figure 3b is the corresponding light-curve; it shows a change from a constant value of 5.75 mag, falling to 6.27 mag at mid-eclipse. The purpose of observing eclipsing binaries is to time their minima, in order to monitor any change in period.[1] For this observation, the O – C (the observed time of minimum, minus the time calculated from an ephemeris) was – 0.0039 days.

Figures 3c and 3d show an observation of MR Cygni, which has a period of 1.68 days, made on JD 2447436, under increasingly misty conditions. This low quality result is shown here to illustrate that the APT can continue to operate under difficult and changing conditions: the APT was still able to centre stars at the end of the observing run. At this time, the sky readings were about 90% of the comparison star readings, and were over 60% greater than the comparison star readings at the start of the run! The accuracy over the entire run is only 0.06 mag, but is better than 0.03 mag up until HJT 0.59. Fortunately the eclipses of MR Cygni are very deep, and Figure 3d shows a useable light-curve, from which an O – C of – 0.0052 days was obtained.

The final example, Figures 3e and 3f, is an observation of ZZ Cephei made on JD 2447442. This star has a period of 2.14 days, and a magnitude change from 8.6 mag to 9.6 mag at mid-eclipse. The plots of Figure 3e show that on two occasions clouds interrupted the observations, and that the APT successfully recommenced taking readings when this cloud had gone away. The first break at HJT = 0.365, and lasted 11 minutes. The second break started at HJT = 0.411, and last 21 minutes. Just before the second break is a very high reading for both the sky and the object. These two readings were omitted from the analysis which produced the light-curve, Figure 3f, which, even though interrupted, allows the O – C of – 0.0044 days to be determined.

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