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General Search for Stars with Rapid Optical Variations: Test Fields

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General Search for Stars with Rapid Optical Variations: Test Fields

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Abstract:

We present a search for stars exhibiting short time-scale optical light variations. Our search employs archival data taken by the ROTSE1 telephoto array in two eight degree fields of view. This is a test study considering two fields which overlap fields previously mined for variables, but with different data and search techniques. Each field was observed for approximately six continuous hours. We employ a general search strategy based on statistical properties of the observed light curves for each object. The analysis is sensitive to sources with variations < 0.25 day and > 0.1 mag and with mean magnitudes between 9.5 mag and 14 mag. We identify 42 variable stars with our search strategy. Of these, 17 were not found by comparison with catalogs of previously acknowledged variables. Within this sample, attempts at classification yield four W UMa systems and two δ Scu stars. The remaining eleven transient detections exhibit incomplete light curves and require further study for classification.

I. Introduction

Stars with varying intensities of brightness, or "magnitude", also known as variable stars, have interested astronomers for hundreds of years. Intensity is "a measure of the light energy from a star that hits 1 square meter in 1 second[1].", and the magnitude is the brightness scale that is based on a constant intensity ratio, which was defined by Hipparchus. The brightest star, Sirius, is magnitude -1.43 and the dimmest star visible to the unaided eye is approximately magnitude 6. The intensity vs. time graph is termed a 'light curve', and variable stars have varying light curves.

Variation in stellar brightness was observed by several cultures, including the Chinese, who saw `guest stars' which were sometimes actual stars that were previously too dim to see by eye. In Western Europe, the first acknowledgement was with the sudden awareness to "new stars" (Latin 'novae stellae'), such as Tycho's star of 1572. Since then, thousands of variable stars have been discovered, and classified based on their peculiarities in variation. The observation of these celestial phenomena have allowed astronomers, both amateur and professional, to learn more about the night sky, particularly objects too dim to see with the unaided eye.

Variable stars are grouped into two major categories: intrinsic, those whose luminosity varies due to pulsating or other alterations in physical characteristics; and extrinsic, those who appear to vary in magnitude due to an eclipsing companion. An eclipsing binary or a variable star can be usually distinguished by distinctive, usual patterns of the intensity versus time light curve. Long period variable stars have been studied for many years because their apparent brightness changes can be easily observed using a telescope. Their periods can last from weeks up to several years.

Short period variation has also been studied, but such stars can require more frequent observations to be well-measured. Such objects have periods that can last from less than an hour to a few days. These types of variables are more commonly the subject of professional research today because of their high energy outputs and patterns of light variation. Two examples of these types of variables are the RR Lyrae (period: 0.2 day ≤ T ≤ 1.0 day, normally 0.5 day) and δ Scuti stars (period: T ≤ 0.3 day, amplitude: 0.01 magnitude ≤ Δm ≤ 0.5 magnitude), which are pulsators and have typically lower luminosity variations and shorter periods than other variables. An example light curve for a pulsating variable is shown in Figure 1, which is discussed in more detail in Section IV. Such stars do not exhibit a static equilibrium between the outward pressure from radiation and the inward pull of gravity. Instead, they release energy when the zone expands and absorb energy when it is compressed, exhibiting complex alternations of heating and cooling, expansion and contraction, and growing more luminous and less luminous.

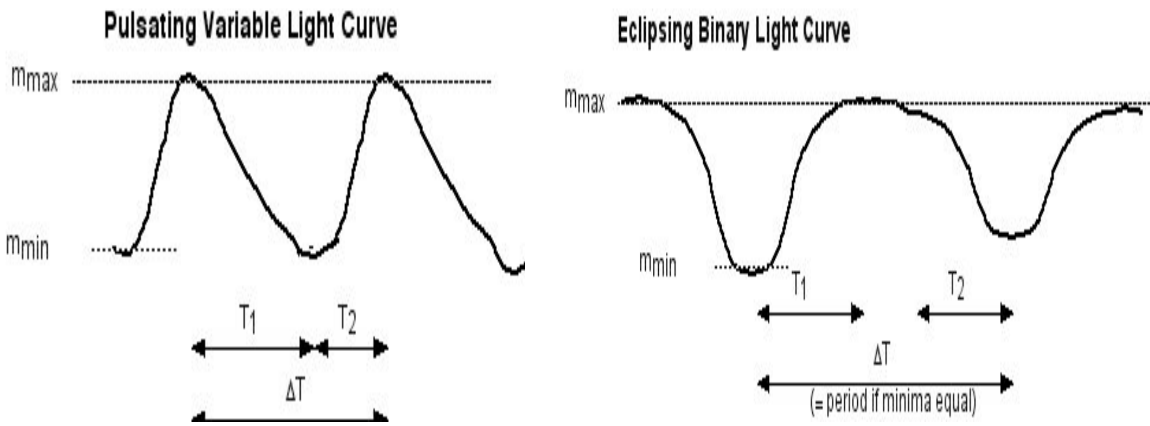

Figure 1: A pulsating variable light curve is shown on the left. The rise (T_1) and fall times (T_2) are generally not equal, and the total period (ΔT) equals the sum of these times. On the right is an eclipsing binary light curve. Dimming and brightening times are similar, and the total period (or half period) is longer than the sum of these times.

Eclipsing binary systems containing stars relatively close or touching each other also exhibit short period behavior. Some have light curves generally characterized by a span of brighter magnitude with one or two dips to a dimmer magnitude. A sketch of such a light curve is shown in Figure 1. Binary systems of the W UMa type contain stars that are so close that the surfaces are in contact and the stars share their atmospheres[2]. The second law of thermodynamics states that the entropy of an isolated system which is not in equilibrium will increase until equilibrium is attained. In a binary star system, heat transfers from the body of higher temperature to the body of lower temperature, therefore the heat, and thus luminosity, is transferred from the more massive star to the less massive one until equal temperatures are acquired. This model of stars is best represented by a light curve that resembles that of a typical binary system, with the dips in magnitude becoming less different from each other.

There are many other types of variable source that exhibit rapid optical light variation. Flare stars exhibit substantial changes in brightness in a few minutes before relaxing to quiescence. Cataclysmic variables can have erratic light curves. Other objects, not stars but active galaxies, can also exhibit rapidly varying light curves.

Many telescopes including the Robotic Optical Transient Search Experiment[3] (ROTSE) observe sources with short time-scale variation. The ROTSE1 telescope provided the data used in this paper. We have pursued a study in an unbiased way to identify the catalog of variable stars with gross characteristics of variation which do not assume a particular kind of physical system. We have employed a basic statistical analysis looking for light curves showing variation during much of a given night of observation.

II. Detector and Data

The ROTSE telescopes were originally created to study the optical light emitted by gamma ray bursts (GRBs), but they are also used to study optical light from numerous types of sources, including variable stars. These small but powerful telescopes are distributed and used internationally. We utilize a subset of data taken between 1999 and 2000 with the ROTSE1 telescope for the purpose of looking for isolated optical bursts associated with GRBs[4].

The ROTSE1 telescope was an array of four Canon telephoto lenses with 8 degree field of view each. These lenses were attached to Apogee AP-10 charge-coupled device (CCD) cameras. A CCD is an array of cells which send an electric signal based on the intensity of the light striking them. The AP-10 was designed initially for ROTSE1 and had a relatively high number of pixels (4 megapixels) and low electronics noise.

The ROTSE telescopes take measurements when photons emanating from a light source are focused to an image on the CCD array of cells. Typically in astronomy, filters are used to restrict to a standard range the wavelengths of light which can strike the CCD. A 'V band' filter restricts the signal to wavelengths in the middle of the optical spectrum, while an 'R band' filter restricts to redder wavelengths. In order to allow the maximum light to strike the CCD, the ROTSE optics do not include filters. The resulting ROTSE1-measured magnitude corresponded approximately to a V or R band magnitude.

The optics typically focus the signals from a point source such as a star to a region approximately 14 arc seconds wide. This is the size of an AP-10 CCD cell. For the brightest stars, signals can spill over to many neighboring cells. This is termed 'saturation' and it creates an undesirably bright and distorted image. As a result, it is difficult to obtain accurate photometry for stars brighter than 10^{th} mag in one minute exposures. Also, the low level electronics noise of the CCD makes it difficult to find or accurately measure the brightness of dim stars. Therefore, ROTSE1 is not sensitive to stars below approximately 15^{th} magnitude, since dim stars are more sensitive to the noise.

Many exposures of sixty seconds were obtained for several consecutive hours over several days, using different fields in April, 2000 and July, 2000 (and other periods), as part of a study for lone optical bursts[4]. We use the data for camera 'b' from the April 14 data, and camera 'a' for the July 6 data as test cases for a future analysis of the entire untriggered sample. These fields are termed '000414b' and '000706a', respectively. Approximately 6 consecutive hours of data were taken in each night. The July data was taken by pointing at two fields alternately in blocks of several minutes. This paper only includes camera 'a' data for one of these two pointings. The images were processed through a chain which corrects for lens vignetting and noise effects, finds stars from the cell readouts in the CCD[5], and provides a precision calibration of positions and magnitudes by comparing to the Hipparcos astrometry catalog[6]. Typically, a position resolution of 1.5 arc seconds is achieved. For bright sources, a magnitude uncertainty of 0.02 magnitudes is achieved.

For each object, many observations can be obtained in one night. With the use of programs written at the University of Michigan using the Interactive Data Language (IDL), these collected data of magnitude are plotted versus time, creating a light curve.

III. Lightcurve Selection

Typically, the fields used for this analysis yield approximately 20,000 observed sources per image. The vast majority of these are non-variable objects, so a search must be made for varying lightcurves. The data stored in the University of Michigan's archive can be extracted through a special lightcurve search called "find_burst." Data is selected by quantifying search "cuts" input by the user based on three statistical criteria calculated in the ways described below. Two of the parameters account for the level of error present in each measurement in the lightcurve.

Amplitude of magnitude variation (Δm): We calculate the difference between the brightest observed magnitude and the dimmest for the light curve:

$$\Delta m = m_{max} - m_{min} . \qquad (1)$$

We require Δm to be greater than some value.

Significance of maximum variation (σ_{max}): We calculate this as the difference in magnitude divided by the estimated errors on the magnitude measurement, added in quadrature:

$$\sigma_{max} = (m_{max} - m_{min}) / (\varepsilon_{max}^{2} + \varepsilon_{min}^{2})^{1/2} . \qquad (2)$$

Here, m means the magnitudes of the light curve, and ε means estimated errors. These errors are statistical errors based on the brightness of the star. This parameter attempts to determine if an observed variation is significant by seeing if it is large compared to the errors on the measurements. We require σ_{max} to be greater than some value to select variable stars which have large, significant variations.

Chi-squared (χ^2): This is calculated as

$$\chi^2 = \sum ((m_i - m_{avg})/\sigma_i)^2 \qquad (3)$$

where the sum is performed over all measurements, i, and m_i and σ_i are the magnitude and estimated error for each measurement, respectively. We calculate m_{avg} to be the average magnitude for the whole light curve. In calculating χ^2, we exclude the single measurement furthest from m_{avg}.

This rejects fake variable light curves where just one measurement is bad. If the star was not variable, its χ^2 would be near 1.0. We require the light curve to be inconsistent with constant brightness, so χ^2 should be large.

To perform a general search, we tried several combinations of cuts on the 000414b data using the above three parameters and counted the number of objects which fell into four general categories. The brightest sources exhibit light curves where most or all of their measurements are saturated, which results in a highly discontinuous light curve, which is not a sign of a variable star. We omit the candidates from our list that are brighter than the magnitude in which this phenomenon is no longer observed. The dimmest sources are strongly affected by noise in the camera and often may not even be identified, resulting in a sparse and erratic light curve with poorly assessed errors on the measurements. We omit stars dimmer than the brightest stars in which we begin observing this phenomenon.

Two types of light curves are found among the remaining candidates. The first type exhibits at least two abrupt, consecutive and opposite changes in brightness, producing one observation substantially different than immediately preceding and following measurements. Usually there must be two such occurrences because the χ^2 requirement rejects candidates with just one isolated bad observation. The other type exhibits a light curve in which most observations are continuous with their immediate neighbors in time. This is not to say they have regular variation: such light curves can be very variable on the timescale of several minutes.

Although it is very difficult, based on general physics principles, to have objects fluctuate by > 0.1 magnitude in brightness in one minute, extreme examples such as gamma-ray bursts have been observed. We keep our search general, while also yielding a purer sample of clear variables, by taking the following approach. We visually inspect the light curves and omit all observations that are discontinuous from their preceding and succeeding observations. In other words, we permit an object to change by several times its error in 1 minute, or we allow it to dim similarly, but we do not permit it to brighten and return back to its original state in three consecutive observations. Such variations can happen rarely due to improperly corrected or noisy pixels, but can produce a large number of false candidates because we are analyzing over 330 observations for 20,000 stars in each field. In making this requirement, we remove isolated bad observations while remaining sensitive to variation on the timescale of a few minutes without bias.

The results of our scan of selections, with the number of rejected bright or dim candidates, and those from bad observations, are shown in Table 1.

Δm	σ_{max}	χ^2	bright	bad obs.	Dim	candidates
0.5	2.0	3.0	0	84	117	2
0.1	0.0	3.0 (‘B’)	24	63	171	15
0.1	0.0	5.0	18	7	15	11
0.1	5.0	1.0 (‘A’)	54	410	195	16
1.0	2.0	5.0	18	0	0	0
1.0	5.0	0.0	0	30	27	0

Table 1: Cuts used in initial lightcurve search in a test on field 000414b. The four columns on the right give the number of backgrounds of different types, and the

number of good candidates. Cuts that are labeled 'A' and 'B', which have no relation to camera names 'a' and 'b', were chosen for variable star selections in this paper.

The rightmost column indicates the number of good variable candidates we observe. The results support the following conclusions. Cuts using $\Delta m > 0.1$ yielded the most good variable candidates: i.e. $\Delta m = 0.1$, $\sigma_{max} = 5.0$, $\chi^2 = 1.0$ yielded sixteen variables out of over 670 light curves. The use of the χ^2 cut significantly reduces the background due to bad observations, with a value of 3.0 (selection 'B') showing the next largest number of good candidate light curves. A selection emphasizing the χ^2 parameter yields a lower background with a similar number of good objects. For field 000414b, selections 'A' and 'B' find a common set of eleven variables candidates, plus five with 'A' only and four with 'B' only.

IV. List of Objects

A total of forty-two candidates are identified in the two fields. For the 000706a field, the 22 identified candidates were varying in at least one other night. All candidates are listed in Table 2 and Table 3, along with their positions and measured lightcurve characteristics. The designations at left follow the form 'ROTSE1 JHHMMSS.SS±ddmmss.s' where 'HH', 'MM' and 'SS.SS' give the RA position in hours, minutes and seconds, and the 'dd', 'mm' and 'ss.s' give the declination analogously. The ROTSE1 magnitude, m_{R1}, is calculated as the average of m_{max} and m_{min}. The time interval ΔT is calculated as the apparent time from maximum to maximum, or minimum to minimum, if a pair of either is apparent. In the case of δ Scu and other pulsating stars, this will be the period. For symmetric W UMa stars and other eclipsing binaries where both dips are deep, it will be half the period. For longer period variables, the quoted value is merely a lower limit as only 6 hours of data were used. Because of the length of time ROTSE1 was observing in the night, there is a natural insensitivity to medium or long time-scale variables.

Also shown in Table 2 and Table 3 are the rise time and fall time of the lightcurve, labeled T_1 and T_2, respectively. These are shown graphically in Figure 1. T_1 is defined as the *shortest* time it takes to rise from the end of a period of minimum brightness to the beginning of a period of maximum brightness. T_2 is defined conversely. These parameters may not correspond to the *full* time to transition from minimum to maximum brightness for the star. But if m_{min} and m_{max} correspond to the actual minima and maxima, these parameters assist in classification efforts, which will be described later.

Source	m_{R1}	Δm	ΔT (days)	T_1(days)	T_2(days)
ROTSE1 J110448.11+353626.6	10.96	0.21	0.20	0.09	0.09
ROTSE1 J113721.25+425544.6	11.49	0.36	0.21	0.10	0.09
ROTSE1 J111345.07+423951.7	11.77	0.15	>0.25	0.16	0.15
ROTSE1 J113334.68+425829.2	11.81	0.28	>0.25	0.11	0.19
ROTSE1 J113536.72+384557.5	12.01	0.47	0.25	0.09	0.20
ROTSE1 J112141.02+433653.1	11.70	0.28	0.25	0.12	0.13
ROTSE1 J111719.74+394303.0	11.98	0.31	0.10	0.08	0.07
ROTSE1 J112541.63+423448.8	12.11	0.35	0.18	0.08	0.09
ROTSE1 J111305.98+402137.7	11.89	0.36	>0.25	0.12	0.17

ROTSE1 J112037.62+392100.3	12.15	0.12	0.07	0.03	0.04
ROTSE1 J111615.06+355027.2	12.66	0.39	0.20	0.09	0.11
ROTSE1 J113928.29+403632.8	12.85	0.50	0.25	0.13	0.12
ROTSE1 J111340.03+424413.8	12.68	0.26	0.21	0.09	0.13
ROTSE1 J111415.57+371825.6	13.02	0.10	0.05	0.02	0.02
ROTSE1 J111105.45+381123.5	13.22	0.21	0.08	0.03	0.03
ROTSE1 J111716.02+385716.9	13.24	0.27	0.20	0.08	0.10
ROTSE1 J112148.80+405938.4	13.25	0.26	0.21	0.07	0.04
ROTSE1 J112009.02+435349.0	11.52	0.17	0.25	0.14	0.12
ROTSE1 J111734.08+410649.0	13.45	0.50	0.10	0.06	0.05
ROTSE1 J110340.78+402617.1	13.80	0.60	0.11	0.07	0.03

Table 2: Candidate variable stars identified by light curve selection in field 000414b. Light-curve properties are tabulated.

Source	m_{R1}	Δm	ΔT (days)	T_1(days)	T_2(days)
ROTSE1 J154029.81+453200.6	13.25	0.39	0.15	0.07	0.05
ROTSE1 J154136.92+515926.5	13.42	0.42	0.075	0.02	0.055
ROTSE1 J154436.45+461922.0	12.54	0.32	0.12	0.04	0.08
ROTSE1 J155028.43+455751.0	12.83	0.29	0.065	0.015	0.05
ROTSE1 J155600.54+494757.0	13.05	0.36	>0.24	0.07	0.11
ROTSE1 J155705.19+500527.6	12.48	0.45	0.16	0.08	0.06
ROTSE1 J155809.25+485742.7	12.58	0.55	>0.24	0.12	--
ROTSE1 J155825.31+492652.1	11.88	0.15	0.16	0.08	0.045
ROTSE1 J155853.75+463548.7	13.34	0.44	0.12	--	0.075
ROTSE1 J160032.12+465526.8	11.70	0.36	>0.17	0.06	0.11
ROTSE1 J160048.24+511648.0	13.32	0.30	0.13	0.06	0.06
ROTSE1 J160121.91+482938.3	12.70	0.55	0.15	0.06	0.06
ROTSE1 J160434.17+504514.5	12.56	0.23	0.18	0.09	0.08
ROTSE1 J160602.27+501111.4	10.23	0.51	0.21	0.08	0.08
ROTSE1 J160653.63+513835.7	13.44	0.67	0.13	0.06	0.07
ROTSE1 J161033.65+514401.1	11.20	0.16	0.20	0.09	0.10
ROTSE1 J161134.29+471612.6	13.52	0.62	0.14	0.05	0.06
ROTSE1 J161321.76+515524.2	11.51	0.45	0.16	0.09	0.07
ROTSE1 J161506.00+445822.3	12.11	0.30	>0.17	0.06	0.08
ROTSE1 J161801.01+511153.0	13.83	0.65	>0.22	0.07	--
ROTSE1 J162004.25+451259.4	9.62	0.07	>0.23	0.23	--
ROTSE1 J162410.37+455527.0	10.29	0.42	0.13	0.06	0.06

Table 3: Candidate variable stars identified by lightcurve selection in field 000706a. Lightcurve properties are tabulated.

Source	Nearest Object	Δr (arcsec)	Object type
ROTSE1 J110448.11+353626.6	HH UMa	0.51	Contact binary[6]
ROTSE1 J113721.25+425544.6	[GGM 2006] 4974567	4.86	Contact binary[7]
ROTSE1 J111345.07+423951.7	TYC 3012-1895-1	0.43	Star
ROTSE1 J113334.68+425829.2	MT UMa	0.30	W UMa[8]
ROTSE1 J113536.72+384557.5	MU UMa	0.55	RR Lyr[8]
ROTSE1 J112141.02+433653.1	MQ UMa	0.87	W UMa[8]
ROTSE1 J111719.74+394303.0	FIRST J111722.9+394253	38.28	Radio[9]
ROTSE1 J112541.63+423448.8	BS UMa	0.80	Algol[10]
ROTSE1 J111305.98+402137.7	MO UMa	0.38	RR Lyr[8]

ROTSE1 J112037.62+392100.3	MP UMa	0.15	Pulsating[4]
ROTSE1 J111615.06+355027.2	[GGM 2006] 7575961	0.13	contact binary[7]
ROTSE1 J113928.29+403632.8	FIRST J113922.2+403640	68.63	Radio[11]
ROTSE1 J111340.03+424413.8	---	---	---
ROTSE1 J111415.57+371825.6	---	---	---
ROTSE1 J111105.45+381123.5	SDSS J111055.84+381055.1	116.74	Quasar[12]
ROTSE1 J111716.02+385716.9	---	---	---
ROTSE1 J112148.80+405938.4	FIRST J112148.9+405909	29.15	Radio[11]
ROTSE1 J112009.02+435349.0	GB6 B1117+4411	99.11	Radio[13]
ROTSE1 J111734.08+410649.0	FIRST J111740.0+410628	69.94	Radio[11]
ROTSE1 J110340.78+402617.1	---	---	---

Table 4: Nearest matches in SIMBAD database to observed candidate variables from the 000414b field. Notes on object classification are given in the rightmost column.

Source	Nearest Object	Δ*r* (arcsec)	Object type
ROTSE1 J154029.81+453200.6	---	---	---
ROTSE1 J154136.92+515926.5	---	---	---
ROTSE1 J154436.45+461922.0	TYC 3483-746-1	1.58	δ Scu[14]
ROTSE1 J155028.43+455751.0	TYC 3490-814-1	0.87	δ Scu[14]
ROTSE1 J155600.54+494757.0	BPS BS 16029-0008	3.92	Star[15]
ROTSE1 J155705.19+500527.6	[GGM2006] 5207106	1.29	contact binary[7]
ROTSE1 J155809.25+485742.7	---	---	---
ROTSE1 J155825.31+492652.1	V* V1023 Her	1.10	W UMa
ROTSE1 J155853.75+463548.7	---	---	---
ROTSE1 J160032.12+465526.8	V* AR Her	1.57	RR Lyr
ROTSE1 J160048.24+511648.0	GSC 03497-01775	2.67	W UMa[16]
ROTSE1 J160121.91+482938.3	[GGM2006] 5208621	0.78	contact binary[7]
ROTSE1 J160434.17+504514.5	GSC 03497-00900	6.64	W UMa[16]
ROTSE1 J160602.27+501111.4	V* V842 Her	1.78	W UMa
ROTSE1 J160653.63+513835.7	---	---	---
ROTSE1 J161033.65+514401.1	TYC 3497-1342-1	0.44	Star[17]
ROTSE1 J161134.29+471612.6	GSC 03491-00010	0.91	W UMa[16]
ROTSE1 J161321.76+515524.2	[GGM2006] 5214166	2.94	contact binary[7]
ROTSE1 J161506.00+445822.3	---	---	---
ROTSE1 J161801.01+511153.0	GSC 03498-01093	1.10	RR Lyr[16]
ROTSE1 J162004.25+451259.4	V* V893 Her	1.91	RR Lyr
ROTSE1 J162410.37+455527.0	TYC 3492-1272-1	0.73	Star[18]

Table 5: Nearest matches in SIMBAD database to observed candidate variables for the 000706a field. Notes on variable classification are in the rightmost column.

Catalog Matching

We have compared these lists to existing objects catalogued in the SIMBAD[19] astronomical database according to their right ascension and declination. Close matches to known or suspected variable stars in the catalog were found for twenty-two candidates. We further check the AAVSO site[20] for remaining objects and find three more matches. All 25 matched candidates proved to be either pulsating variables or eclipsing binaries. Most of these were identified using ROTSE1 data in previous publications. Of the 25 matched candidates, twelve are recent, unconfirmed identifications. We present these lightcurves in this section. From the previously acknowledged twenty-five, we have seventeen other candidates that are newly identified transients. We discuss these seventeen cases in the next section.

Recently Identified Eclipsing Binaries

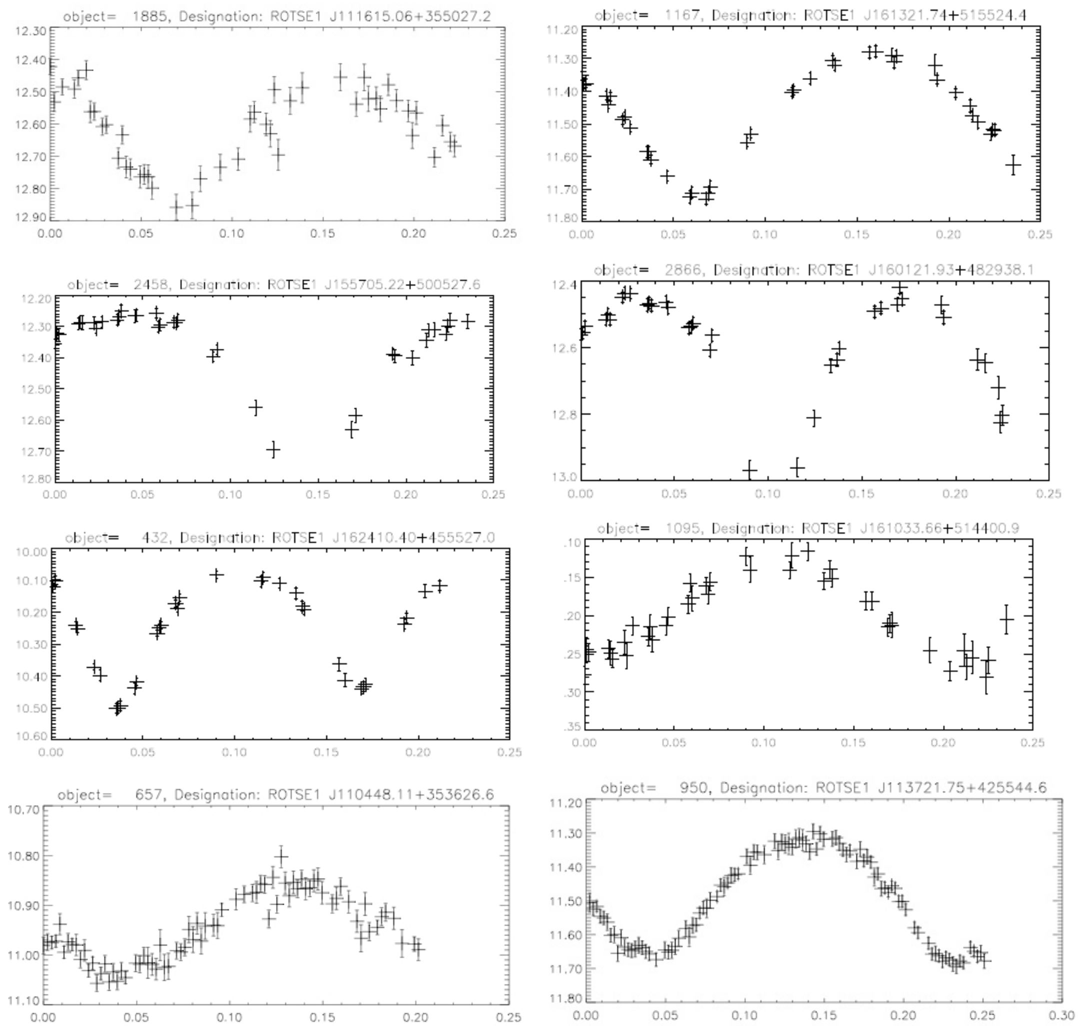

Figure 2: Eight single-night light curves for previously suspected contact binaries. Plotted errors are statistical + systematic. The *x*-axis represents the time of observation in days, while the *y*-axis represents the magnitude of an observation.

From our original 25 previously identified candidates, there are sixteen candidates matching previously identified or suspected eclipsing systems. Eight of the sixteen candidates are not listed as definite classifications in the SIMBAD catalog, although there are claims these are W UMa systems[6],[7]. The light curves for the eight suggested variables are shown in Figure 2. We measure T_1 to be similar to T_2 and ΔT to be a little larger than T_1+T_2 for these objects, which suggest W UMa classification. These light curve data therefore support the existing claims.

Recently Identified Pulsating Variables

The remaining nine of twenty-five previously identified candidates are identified as pulsating variables. Four of them are not clearly categorized in SIMBAD. Their lightcurves are shown in Figure 3. One of the four candidates (ROTSE1 J112037.63+392100.3) is listed as a variable of general 'pulsating' classification in the SIMBAD catalog. This is based on a preliminary identification of this as a δ Scu star[4]. Three and a half more periods are evident in the lightcurve in Figure 3. At least two periods are evident for two of the other candidates. Considering that $T_1 \neq T_2$ and $\Delta T = T_1 + T_2$, these data support the claims of these being of δ Scu type. The last of the four stars is an RR Lyr star for which we observe a partial lightcurve consistent with this classification.

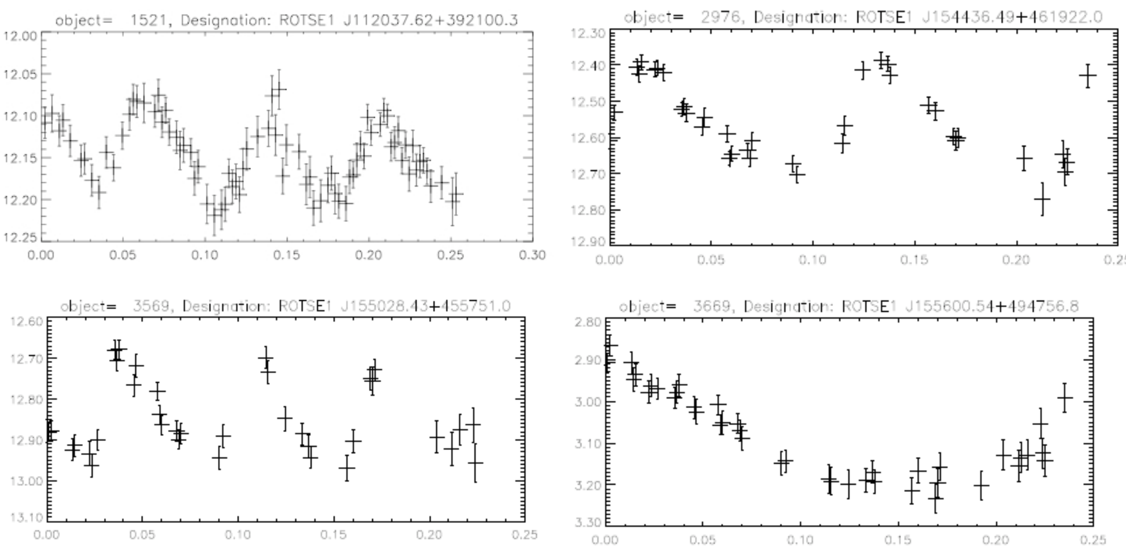

Figure 3: Four single-night light curves for previously suspected pulsating variables. Plotted errors are statistical + systematic. The *x*-axis represents the time of observation in days, while the *y*-axis represents the magnitude of an observation.

V. Analysis of Unmatched Sources

Our seventeen remaining candidates are previously uncatalogued as variable sources. We divide these variables into four categories: eclipsing candidates, pulsating candidates, incomplete smooth lightcurves, and irregular variables. This is based upon the lightcurve characteristics in Table 2 and Table 3. In order to assist identification of the candidates, it is useful to examine multiband photometry of these objects. In order to do this, we consulted the IPAC[21] online catalog to extract infrared or optical band magnitudes. For field 000414b, one of the candidates matching a radio source, ROTSE1 J112148.80+405938.4, has been suggested to be a variable of potentially pulsating type[4]. The lightcurve presented here does not support the pulsating classification, but it does confirm the variable nature of the source.

Previously Uncatalogued Eclipsing Candidates

Eclipsing candidates are identified by exhibiting clear minima and maxima which allow a full set of light curve parameters to be calculated in Table 2 and Table 3. We select those variables where T_1 and T_2 are similar in magnitude, and where $\Delta T > T_1+T_2$. Their light curves are shown in Figure 4.

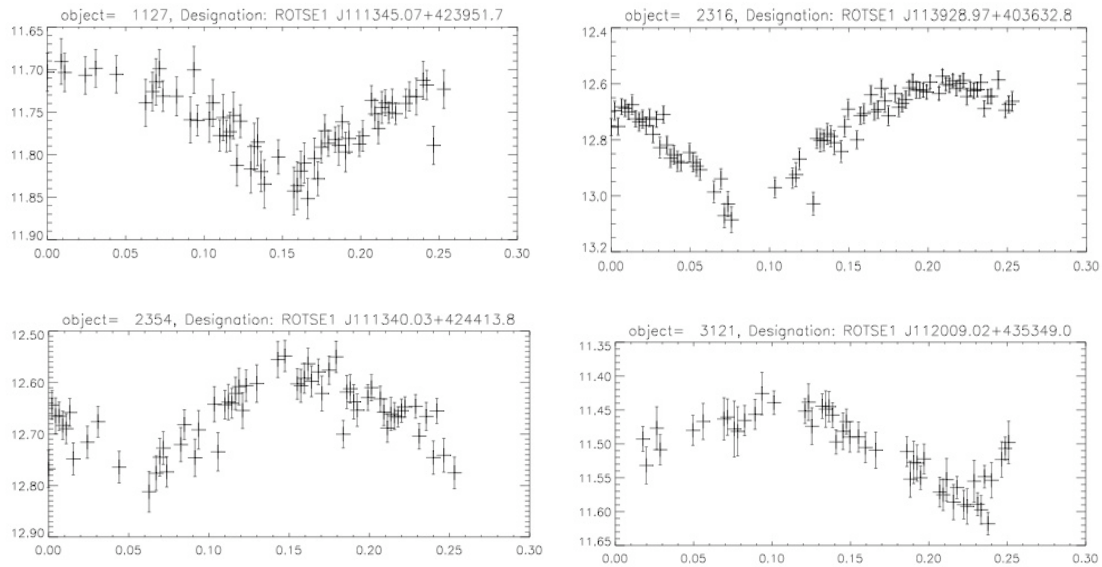

Figure 4: Single-night light curves for eclipsing binary candidates without a known variable match. Plotted errors are statistical + systematic. The *x*-axis represents the time of observation in days, while the *y*-axis represents the magnitude of an observation.

The estimated periods and infrared band magnitudes for these candidates are given in Table 6. The infrared band magnitudes J, H and K cover ranges of progressively longer wavelengths, with J being near-infrared and K being far-infrared wavelengths. All four objects satisfy the selections used in Ref. 7 to identify W UMa stars: $0.26 < T < 0.6$, m_{R1}-J ≤ 3.0, H-K ≤ 0.35, and $0.71-1.45T <$ J-H $< 0.96-1.45T$. The amplitudes of variation for these stars tend to be lower than was typical in that search.

Source	*T* (days)	J	H	K	m_{R1}-J	H-K	J-H
ROTSE1 J111345.07+423951.7	0.55	10.925	10.735	10.660	0.84	0.08	0.19
ROTSE1 J113928.29+403632.8	0.50	11.940	11.697	11.625	0.91	0.07	0.24
ROTSE1 J111340.03+424413.8	0.42	11.422	11.165	11.103	1.26	0.07	0.25
ROTSE1 J112009.02+435349.0	0.5	10.427	10.234	10.147	1.09	0.08	0.20

Table 6: Period, infrared band magnitudes and colors for four new W UMa candidates. J through K bands are from 2MASS[22].

Previously Uncatalogued Pulsating Candidates

The pulsating candidates are identified by exhibiting minima and maxima. These candidates satisfy $T_1 \neq T_2$ and ΔT approximately equal to T_1+T_2. Their lightcurves are shown in Figure 5. ROTSE1 J111415.57+371825.6 is not a clear variable detection. The second half of the lightcurve is very erratic, suggesting an instrumental problem, while the earlier 3 hours may indicate a δ Scu with ~0.1 mag amplitude and 0.05 day period at the edge of sensitivity. A firm identification will require examining more data.

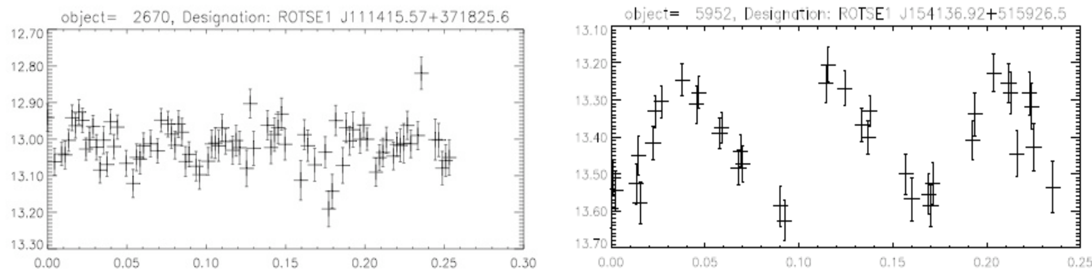

Figure 5: Single-night light curves for objects without a match but which may be pulsating variables. Plotted errors are statistical + systematic. The *x*-axis represents the time of observation in days, while the *y*-axis represents the magnitude of an observation.

Color information for ROTSE1 J154136.92+515926.5 and ROTSE1 J111415.57+371825.6 is given in Table 7. Pulsators of δ Scu type are expected to reside in spectral categories A0-F5, which corresponds roughly to -0.1 < B-V < 1.0. We do not have B and V magnitudes for these two objects, but obtain B and R by averaging the two measurements from the USNO-B1 catalog. If we assume that B>V and V>R, then B-R is an upper limit on B-V. These quantities are consistent with both stars being δ Scu stars.

Source	*T* (days)	B	R	B-R
ROTSE1 J111415.57+371825.6	0.05	13.68	13.00	0.68
ROTSE1 J154136.92+515926.5	0.08	13.39	12.67	0.72

Table 7: Period, optical band magnitudes and color for two δ Scu candidates. B and R band magnitudes are from USNO-B1.

Previously Uncatalogued Stars with Continuous, Incomplete Variations

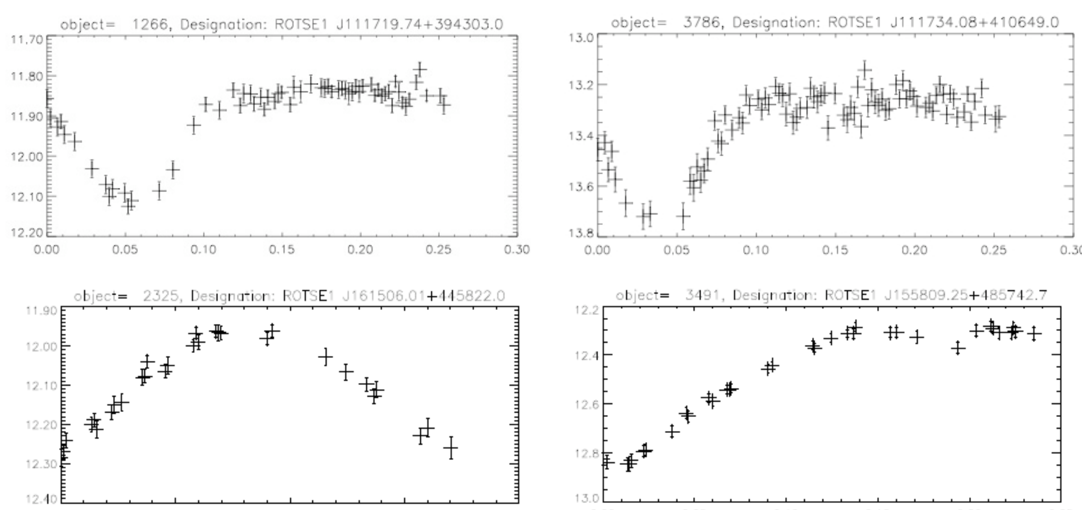

Figure 6: Single-night light curves for objects without a transient match. Lightcurves appear to be incomplete segments from regular variables. Errors are statistical + systematic. The *x*-axis represents the time of observation in days, while the

y-axis represents the magnitude of an observation.

Four variables with incomplete smooth lightcurves are shown in Figure 6. These lightcurves are missing some information needed for a preliminary classification. In all cases, we cannot properly estimate T_2 or ΔT, and either the maxima or minima are missing. Although they appear clearly distinct from the irregular variable category, use of further data will be needed to establish these identifications.

Previously Uncatalogued Irregular Variable Candidates:

Seven of the candidates appear to fall into an irregular variable category. These lightcurves are shown in Figure 7. We will present further results on these objects in a future study.

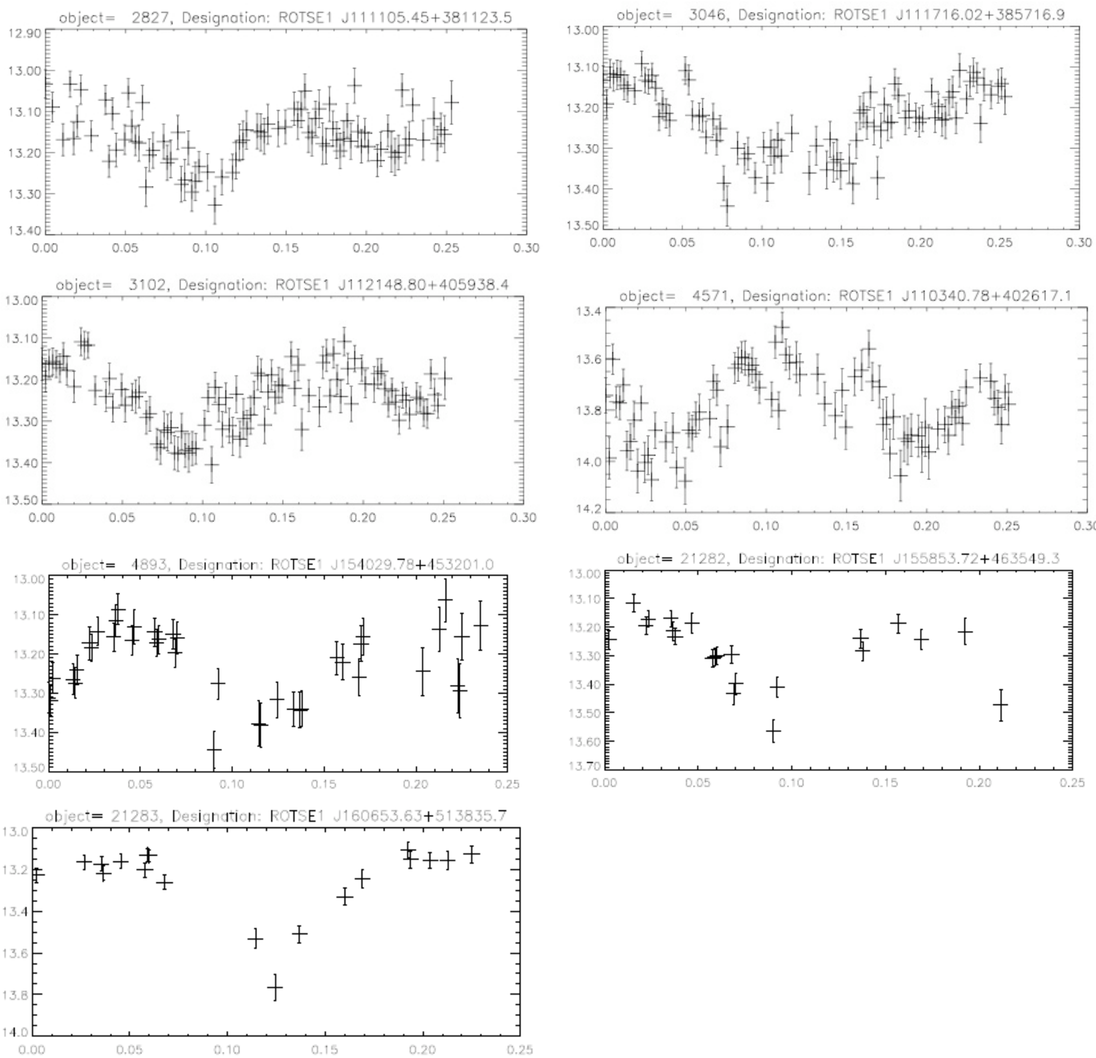

Figure 7: Single-night light curves for objects without a variable match and exhibiting irregular variations. Plotted errors are statistical + systematic. The *x*-axis represents the time of observation in days, while the *y*-axis represents the magnitude of an observation.

VI. Results

We have performed a search for optically variable sources in two fields with one night each of ROTSE1 data and identified 42 variable candidates. Of these, 10% were previously discovered with non-ROTSE1 data, and 17 were not previously catalogued as variables. We provide light curves to support classification for twelve W UMa, δ Scu and RR Lyr variables whose identification may not be settled. We identify four previously unidentified W UMa contact binaries and two δ Scu stars. We also identify 11 candidates that are clearly variable but require more data to ascertain their physical characteristics.

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