Contact Binary Stars in the ROTSE-I Survey

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ABSTRACT

In this work I present a description of a large new sample of contact binary stars extracted in a uniform manner from sky patrol data taken by the ROTSE-I telescope. Extensive ROTSE-I light curve data is combined with J, H, and K band near-infrared data taken from the Two Micron All-Sky Survey (2MASS) to add color information. Contact binaries candidates are selected using the observed period-color relation. Candidates are confirmed by visual examination of the light curves. A new $J-H$ period-color-luminosity relation is derived and used to obtain distance estimates for all objects, yielding an estimate for the contact binary space density of $1.7 \pm 0.6 \times 10^{-5} \text{pcs}^{-3}$. To supplement these findings, I also present preliminary work on the extraction of variable stars from two fields in the ROTSE-III sky patrol data. Much of this work was recently published as Gettel, et al. (2006).

1. INTRODUCTION

W UMa-type contact binaries are eclipsing systems in which the two component stars are in physical contact. Both overflow their Roche lobes, as seen Figure 1, and form a common envelope of material (Lucy 1968), which causes the stars to have the same surface temperature to within 100-200 K. They are formed from nearly normal main-sequence stars with spectral types usually between F and K. Typical mass ratios are between $q \approx 0.2 - 0.5$, but reported values are almost as high as unity, and as low as 0.066 (Rucinski, et al. 2001). Their periods range from 0.22 days to 1.5 days, with most systems having periods between 0.25 – 0.5 days. Contact binaries are divided into two categories: A-type systems, in which the primary minima corresponds to the eclipse of the larger component, and W-type
systems, in which the primary minima corresponds to the eclipse of the smaller component (Pribulla, et al. 2003).

Contact binary evolution is not yet well understood. The traditional Thermal Relaxation Oscillation model states that two stars with a common envelope cannot be in stable equilibrium. Rather, the system oscillates between full contact, during which the eclipses have nearly equal depth, and marginal contact (Flannery (1976), Lucy (1976), Robertson & Eggleton (1977)). Other models propose that a short period detached binary system undergoes angular momentum loss (AML) through a magnetized wind with a single mass-ratio reversal (Stepien 2006), or that contact binaries evolve through a combination of AML and mass-ratio oscillations (Qian 2003).

Contact binary light curves often display long-term period changes with shorter, sinusoidal variations (Qian 2005). Secular period decrease is thought to be caused by mass transfer from the primary to the secondary component, coupled with AML. Over time, AML will cause the component stars will merge into a single, rapidly rotating blue straggler (Rasio & Shapiro 1995). The shorter scale cyclic period variations could be due to the presence of a third body, or to the system’s cycle of magnetic activity (Qian 2003).

The initial formation of contact binary systems is even less well understood. Pribulla & Rucinski (2006) state that it is not possible for a system with a period under 1 day to be created in binary form. However, if a more distantly spaced binary interacts with a third body, it is possible for most of the angular momentum to be allocated to the most distant companion. The same study found that $59 \pm 8\%$ of observed systems in the northern sky have tertiary components. This lower limit suggests that possibly all contact binary systems have a third component, which may be necessary for their formation.

One source of AML in a system already in contact is magnetic braking by stellar wind (Qian 2001a). This is thought to cause coronal activity, and the well known magnetic
activity of contact binaries, including x-ray emission. The fraction of W UMa stars that correspond to known x-ray sources is the subject of a companion project, Geske, et al. (2006).

The similar temperatures of the component stars give contact binaries unique and useful properties. Through a combination of Kepler’s third law and the radius-color relationship for main-sequence stars, this common temperature leads to a period-color-luminosity relation (Rucinski (1994), Rucinski & Duerbeck (1997)). Also, their close proximity produces continuously varying light curves, making them detectable at a large range of inclinations. The period-color-luminosity relation combined with their ease of detection make contact binaries useful tracers of distance and galactic structure, especially on small scales (Rucinski 2004).

Contact binaries are known to be quite common among variable stars, though their space density is still debated. Early estimates range from $10^{-6}$ pc$^{-3}$ (Kraft 1967) to $10^{-4}$ pc$^{-3}$ (van’t Veer 1975). More recent estimates include those of Rucinski (2002), who found a density of $1.0 \times 10^{-5}$pc$^{-3}$, or 1/500 main-sequence stars, in the solar neighborhood. This conflicts with a previous estimate of 1/130 main-sequence stars made using OGLE-I data for more distant stars in the galactic disk (Rucinski 1998b), and may be an indication of significant variability in the contact binary fraction through the galaxy.

Currently, the General Catalog of Variable Stars (GCVS) (Samus et al. 2004) labels 845 stars as EW type variables; W UMa variables with periods less than 1 day and nearly equal minima. However, GCVS classifications are not entirely secure. Other contact binary catalogs include that of Pribulla, et al. (2003), which contains 361 galactic EW and EB type variables, each previously identified by another catalog such as the GCVS. Contact binaries included had either light curve or good spectroscopic data available. Also, analysis of the ROTSE-I variability test fields (Akerlof, et al. 2000) found 382 contact binary candidates
within about 2000 deg$^2$, identified by their light curve shape and period. Periods and light curve data were provided for all of these ROTSE-I objects.

This paper details the results of a search for contact binary stars in the ROTSE-I sky patrols, a task undertaken ultimately to identify these contact binaries among known x-ray sources and calculate their contribution to the x-ray background. A catalog of 1022 contact binary stars was produced from the ROTSE-I sky patrols, 836 of which are not found in the GCVS, SIMBAD database, Pribulla catalog or ROTSE-I test fields. Light curve data, periods, and distance estimates were obtained for each object. These objects passed a rather stringent selection process and have high quality light curves, so their classification is relatively secure. The completeness of this catalog for the regions surveyed is estimated to be about 34%, with the remaining objects lost to data quality cuts. Near infrared observations of these objects drawn from the Two-Micron All-Sky Survey (2MASS) allow us to create a NIR period-color-luminosity relation and to estimate distances to each object. An estimate of the space density of these objects is also made. In addition, a preliminary investigation is made of the photometric data quality and variability of objects in two ROTSE-III sky patrol fields.

2. OVERVIEW OF ROTSE-I SKY PATROL DATA

Optical variability data were obtained by the ROTSE-I robotic telescope$^1$. ROTSE-I was a four-fold array of Canon 200 mm f/1.8 lenses, each equipped with an unfiltered 2048x2048 pixel Thompson TH7899M CCD. At this f-number, the 14 $\mu$m pixels of the CCD subtend 14.4$''$ on the sky. The combined array imaged a continuous 16$^\circ$x16$^\circ$ field of view. ROTSE-I, designed to pursue real-time observations of gamma-ray bursts, spent most of

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$^1$For more information about ROTSE see http://www.rotse.net
the time from March 1998 until December 2001 patrolling the sky. The very large ROTSE-I field of view allowed it to image the entire available sky twice each night, taking a pair of 80 s images during each visit. Typical limiting magnitudes range from $m_v = 14.5 - 15.5$, depending on sky conditions. During its operating life, ROTSE-I amassed a 7 terabyte time domain survey of the night sky. Since being disassembled in 2002, the ROTSE-I lens and camera assemblies have been reborn as elements of the Hungarian Automated Telescope Network (HAT-net; Bakos, et al. (2004)).

Initial studies of ROTSE-I sky patrols were reported in Akerlof, et al. (2000). Though this work examined only three months of observations covering just 5% of the sky patrol area it revealed nearly 1800 bright variable objects, most of which were previously unknown. More recently, light curve data from a full year of all ROTSE-I sky patrols has been released publicly by Wozniak, et al. (2004) as the Northern Sky Variability Survey (NSVS), which is available through the SKYDOT website at Los Alamos National Lab (skydot.lanl.gov). This work includes the entire region north of -30° declination, though coverage is neither perfectly uniform nor absolutely complete. Many more light curve points are available for sources at high declination than at low. Completeness is reduced in regions of very high stellar density.

All optical light curves used in this paper are drawn from the NSVS. Details of the SExtractor (Bertin & Arnould 1996) based reductions and relative photometry corrections of ROTSE-I data for inclusion in the NSVS catalog, along with maps of source density and number of good light curve data points, are presented in Wozniak, et al. (2004).
3. SELECTION OF SHORT PERIOD VARIABLES IN ROTSE-I DATA

3.1. The Welch-Stetson Technique & Phasing

Selection of variable objects from the NSVS light curve database follows the methods outlined in Akerlof, et al. (2000). For each object, available data are examined for all good coincident pairs of observations. For this purpose, ‘good’ points were defined at two levels, one more stringent than the other. Cuts are made by examining the measurement flags described in Wozniak, et al. (2004). The tight cuts require no processing flags except the SExtractor ‘blended’ flag, indicating that an object is the result of a deblending procedure. In addition to the ‘blended’ flag, the second set of loose cuts allow the inclusion of points that have ‘nocorr’ and ‘patch’ flags, indicating that the relative photometry correction of an object could not be estimated, or that the map of corrections was patched to obtain the value for that object. Both sets of cuts are quite restrictive and yield a set of very well measured light curves.

For each object with at least 20 pairs of observations passing the tolerant cuts, the modified Welch-Stetson (Welch & Stetson 1993) variability index $I_{val}$ was calculated as described in Akerlof, et al. (2000). This method examines the variation of individual magnitudes from the mean magnitude. It is expected that for a real variable, pairs of observations will show a correlation between these variations that is absent in a stable object. The distribution of variability indices seen in a representative sample of the data is shown in Figure 2. This distribution is roughly Gaussian with a mean value of 0.227 and a width $\sigma = 0.11$. Every object with $I_{val}$ greater than one, about 7 $\sigma$ from the mean, is accepted as a variable. From a list of $1.43 \times 10^7$ input light curves, 63,665 are selected as variable by these criteria, a variability fraction of 0.45%. The total number of detectable variables, as can be seen from the $I_{val}$ distribution plot, is substantially larger.
Most of the variable objects identified are long period variables, with periods of 10 days or more. To identify short period variables within this set, a simple light curve roughness parameter similar in spirit to the WS variability parameter was calculated. For this calculation, triplets of consecutive pairs of observations spaced by no more than five days are considered. For each of the outer pairs in a triplet the mean magnitude is calculated. Using these, the mean magnitude for the middle pair is predicted by linear interpolation. Next, the residual between actual and predicted magnitude for each observation in the central pair is compared to the error in its magnitude.

\[
\delta_1 = \frac{m_1 - m_{predicted}}{\sqrt{\sigma_1^2 + 0.04^2}}
\]

\[
\delta_2 = \frac{m_2 - m_{predicted}}{\sqrt{\sigma_2^2 + 0.04^2}}
\]

An additional uncertainty of 0.04 magnitudes is added in quadrature to the measurement errors to reduce the sensitivity of this parameter to small non-Gaussian errors. Then the sum of the absolute values of the products of these scaled residuals is divided by the number of predicted points, to construct the roughness parameter:

\[
R = \frac{1}{\sqrt{N_{triplets} \times (N_{triplets} - 1)}} \Sigma_{triplets} \sqrt{\left| \delta_1 \times \delta_2 \right|}
\]

The distribution of this roughness parameter for all of the 63,665 variables is shown in Figure 2. For variables with periods longer than a few days, this roughness parameter is distributed in a approximately Gaussian manner, with a mean of 0.4 and a width \( \sigma = 0.22 \). To construct a list of candidate short period variables those with \( R > 1.0 \) are selected. The total number of such candidates is 17,508.

Each of these candidate short period variables is then passed to the cubic spline phasing code described in detail in Akerlof, et al. (1994). This code provides best-fit periods, period error estimates, and spline fit approximations for light curve shapes. For each variable, the quality of this phasing is tested by measuring an analogous roughness parameter for
the phased light curve. For most eclipsing systems the period identified is actually half
the real period. If the light curve is symmetric (as is the case for full contact binaries),
the phased light curve is very smooth with this period. If the minima are not symmetric,
the light curve will appear ‘rough’ with this period, but smooth when tested at twice the
period. As a result, the light curve smoothness is measured for both the identified period
and for twice the period, and accept as well phased light curves which have acceptably
small roughness with either period. Examples of this are shown in Figure 3. Comparison of
this folded roughness to the original roughness allows for the definition of a sample which
is well-phased. Of the 17,508 short period candidates, 16548 have a phased roughness
parameter less than 1.5 when phased at either the derived period or twice the derived
period. These objects are deemed to be confidently phased.

3.2. Combination of NSVS and 2MASS data

ROTSE-I data is unfiltered, so although there is excellent light curve information, any
color information is absent. To ameliorate this, the ROTSE-I light curve information is
combined with J, H, and K band near-infrared data drawn from the Two Micron All-Sky
Survey (2MASS). This combination is especially apt because 2MASS data is significantly
deeper than ROTSE-I data. As a result 2MASS measurements for all ROTSE-I objects are
rather precise.

2MASS observations are taken simultaneously in all three bands, and are reported
for a single epoch. Combining these data with ROTSE information provides three colors,
m_{ROTSE}–J, J–H, and H–K, where m_{ROTSE} is the mean apparent magnitude in the unfiltered
ROTSE-I band. Color-color plots for all variables and for short period variables are shown
in Figures 4 and 5. The 2MASS observations correspond to random phases of the ROTSE
light curves, generating uncertainty in each value of m_{ROTSE}–J and causing the horizontal
spread in the $m_{\text{ROTSE}}$-J v. J-H plots. The J-H and H-K color measurements do not suffer this dispersion, and the measured J, H, and K magnitudes can be simply compared to determine single epoch object colors.

To identify the proper 2MASS counterparts the positions of all NSVS variables are passed to the 2MASS database query tool at IPAC\textsuperscript{2}. Since ROTSE-I pixels are relatively large, there can be minor ambiguity in the identification of the correct corresponding 2MASS source. This problem is limited by the fact that ROTSE-I variables are all rather bright and hence their sky density is not especially high. When there is more than one match, the chosen 2MASS matching object is the nearest object with $m_{\text{ROTSE}} - J > 0$.

Color-color plots for all the variables and those identified as short period by the methods described above are shown in Figures 4 and 5. It is clear by comparison that the short period candidates are a special, predominantly blue, subset. Visual examination of the few red ($m_{\text{ROTSE}} - J > 3.0$) short period candidates shows them to all be long period variables with relatively large light curve roughness. As a result, the short period variable candidate list is further refined by requiring $m_{\text{ROTSE}} - J \leq 3.0$ and $H - K \leq 0.35$. These cuts leave a total of 16046 phased short period variable candidates.

4. IDENTIFYING CONTACT BINARY STARS IN ROTSE-I DATA

4.1. The Period-Color Relation for Contact Binaries

Contact binary stars are known to exhibit a period-color relation. As shown in Figure 6, there is a dense patch of short period variables which displays a period-color dependence. Comparison to the location in period-color space of known contact binaries suggests that

\textsuperscript{2}http://www.ipac.caltech.edu/2mass/
this excess is largely due to these stars. To generate a list of potential contact binaries, cuts were made defining the region:

\begin{equation}
0.26 < \Gamma < 0.6
\end{equation}

\begin{equation}
0.71 - 1.45\Gamma < J - H < 0.96 - 1.45\Gamma
\end{equation}

selecting a total of 5179 objects. Here, the period (\(\Gamma\)) is twice the value returned by the phasing procedure, and so represents the true period for contact binaries.

Interspersed throughout the region of period-color dependence is a background of variables which are not contact binaries. Upon scanning the light curves, many of the 5179 candidates were found to be other types of variables. In addition, many of the candidates with lower \(I_{\text{val}}\) parameters had small-amplitude light curves and large photometry errors, making classification difficult.

To ensure an essentially pure sample of contact binaries, further data quality cuts were made to select only the very well measured light curves. A cut at \(I_{\text{val}} > 2\) eliminated 62% of candidates, many of which had relatively indistinct light curves. An additional cut was placed on the roughness of the light curve when phased at the true period, requiring this to fall in a range from 0.25 to 0.75. This removed an additional 14% of the candidates, mostly variables which were clearly not contact binaries and so had light curves characterized by a different phased roughness value. The remaining 1238 candidates were individually scanned and 66 objects that did not appear to be contact binaries were removed. 9 of these appeared to be RR Lyrae stars and 3 appeared to be ordinary eclipsing binaries. The other removed light curves were not sufficiently well measured to be easily identified and many appeared to have asymmetric brightening and dimming phases. After these cuts, a sample of 1172 contact binaries remains.

Finally, due to the overlap in the fields, some of the objects appear two or more times in the catalog. In these cases, data from the field that provided the most good observations
were selected for use in the catalog. After discarding the duplicate objects, a catalog of 1022 contact binaries remains. Based on visual inspection and comparison to existing catalogs, this sample is expected to be rather pure, with no more than 5% contamination of pulsating variables such as RRc stars. A sample of this catalog is given in Tables 1 and 2.

4.2. Tests of Selection Efficiency

This section describes efforts to determine the selection efficiency for contact binaries. I test the catalog of Pribulla, et al. (2003) for inclusion in the catalog. Due to the data quality cuts, it is expected that the catalog will be most complete for nearby objects, but it is not possible to use a volume-limited sample, as their catalog does not contain distance estimates. Instead, I use a magnitude-limited sample, restricting the analysis of completeness to objects brighter than 12.5 magnitudes. This corresponds roughly to the objects whose distance estimates placed them within 300 pcs. In the Pribulla catalog, there were 274 known contact binaries with maximum apparent magnitude values less than 12.5. A total of 148 of these were located within the NSVS survey region. Among these, 50 objects were included in the final catalog, resulting in a total completeness level of about 34%. This low efficiency reflects the stringent cuts made to ensure a pure sample.

The remaining objects were not included in the catalog for a variety of reasons. The 148 Pribulla stars that could reasonably have been observed were compared to the list of 16548 well-phased short period variables. There were 88 matches, about 25% of which fall outside of the period-color cuts we have defined. Another 20% do not pass the data quality cuts. The remaining 60 objects do not have enough good observations, either because they fall in regions of high stellar density (near the galactic plane) or because they are in regions less well observed in the NSVS.
5. ESTIMATING DISTANCES TO CONTACT BINARIES FROM ROTSE-I

This section describes the calibration of a near-infrared period, color, luminosity relation for contact binaries. I also discuss applying this relation to estimate distances to all of the contact binaries.

5.1. Determining $V_{\text{max}}$

For contact binaries, the maximum magnitude $V_{\text{max}}$ is independent of inclination, and hence is an appropriate measure of apparent magnitude for distance estimation. The $V_{\text{max}}$ of each object was determined from its light curve. First, the light curves were phased, then the observations dimmer than the mean magnitude were removed and a parabola was fitted to the remaining points. The vertex of the parabola was taken to be the maximum magnitude. If the fit failed, $V_{\text{max}}$ was taken to be the average magnitude of the brightest observations. Figure 7 shows the parabola fit used in obtaining $V_{\text{max}}$ for eight random objects in the catalog.

To obtain the error on $V_{\text{max}}$, this fit was bootstrap re-sampled 10000 times. Of the N datapoints for each star, a random sample of size N was selected, with repetitions, creating numerous slightly different fits from a single light curve. The resulting distribution of $V_{\text{max}}$ values was histogrammed using the optimal bin size and then fitted to a Gaussian. The mean of the Gaussian was taken to be $V_{\text{max}}$ and its standard deviation was taken to be the error on $V_{\text{max}}$. Examples of the Gaussian fit to the histogram are given in Figure 8.

For most objects, the mean of the Gaussian differed by less than 0.1 magnitude from the median of the bootstrap distribution. However, in a few the difference was much larger. These objects also had atypically large standard deviation for their Gaussian fits. In this case, $V_{\text{max}}$ values at 4 $\sigma$ of the bootstrap distribution and beyond were thrown out, and
the recalculated median and standard deviation were used as $V_{\text{max}}$ and its uncertainty, respectively.

5.2. Calibrating the Period-Color-Luminosity Relation

To obtain distance estimates, a sample of 38 previously known contact binaries was used. Each of these objects has parallax data from the Hipparcos catalog (ESA 1997), in addition to 2MASS color data and a period derived from its light curve. Reference distances were calculated from parallax, then three objects were removed due to poorly determined distance estimates. Absolute magnitude values were then determined from parallax.

Rucinski & Duerbeck (1997) established a relation between the period, $B-V$ color and absolute magnitude of a contact binary system. Contact binaries are close to the main sequence and so have a mass-radius dependence. Because the stars are in contact, the period of the system depends on the radii of the component stars, so the color of the system depends on its period.

I derived a similar relation using the $J-H$ color obtained by 2MASS. A plane was fitted to the period, color and luminosity data of the 35 calibration stars, which were weighted by distance uncertainty. The coefficients of this initial fit were sampled until a minimum value of $\chi^2$ was found and these new coefficients were selected to be the proper fit. The uncertainty on these coefficients was derived from their pattern of variation with increasing $\chi^2$. The observed relation can be written:

$$M_{\text{ROTSE}} = (2.20 \pm 0.66) + (0.88 \pm 1.01) \log(\Gamma) + (7.99 \pm 2.33)(J - H).$$  \hspace{1cm} (6)

Used in combination with the standard magnitude-distance formulas, I obtain the relation

$$\log(D) = 0.2V_{\text{max}} - 0.18 \log(\Gamma) - 1.60(J - H) + 0.56$$  \hspace{1cm} (7)
where distance is in parsecs and $\Gamma$ is the true period in days. When used to calculate
distances for the sample, all but about 23% had values within 80 pcs of their distances from
parallax. The median difference was 36 pcs and the maximum was 273 pcs. The comparison
between the calculated distance and the distance from parallax is shown in Figure 9. This
relation was then used to obtain distance estimates for the full set of contact binaries.

5.3. Comparison to Other Calibrations & Tests for Third Parameters

Rucinski and Duerbeck’s original period-color-luminosity relation was then applied
to the calibration sample, which has $B-V$ colors from the Hipparcos data. The absolute
magnitude estimates obtained with their relation tend to be lower and the distance
estimates slightly higher than those obtained with the relation I derived. This can be seen
in Figure 10. All but about 22% of the distance estimates given by the $B-V$ relation
were within 80 pcs of the references distances. The median difference was 39 pcs and
the maximum was 400 pcs; results which are comparable to those obtained using $J-H$.
Rucinski and Duerbeck used a calibration sample of 40 systems, only slightly larger than
mine. However, those systems have a larger range of period, $0.24 < \Gamma < 1.15$ days versus
$0.24 < \Gamma < 1.06$, and color, $0.26 < B-V < 1.14$ versus $0.28 < B-V < 0.87$, than do the 31
systems in the ROTSE calibration set for which $B-V$ values are known. Therefore their
calibration set may be more representative of the entire class of contact binaries.

Earlier absolute magnitude calibrations have included additional dependences, such as
the metallicity and the orbital inclination of the system. To test for sources of dispersion in
the period-color-luminosity relation, the distance residuals were plotted against all available
colors: $m_{ROTSE}-J$, $J-H$, $H-K$, and $B-V$; as well as $\Gamma$, $V_{max}$, $I_{val}$, and the amplitude of
the light curve. Any dependence on these last two parameters may be representative of
a dependence on orbital inclination. Any relationship between the distance residuals and
period or J-H would indicate that absolute magnitude depends more strongly on those parameters than the calculated period-color-luminosity relation suggests. However, no significant dependencies were found. See plots in Figures 11 and 12.

6. ESTIMATING THE SPACE DENSITY OF CONTACT BINARIES

The cumulative number of detections should increase with the distance to the sources cubed, if contact binaries are homogeneously distributed. To calculate the space density of contact binaries, the sky coverage of the contact binary catalog must first be estimated. The analysis is limited to the sky north of $0^\circ$ declination, which was more thoroughly observed. This yields an area of 17458 deg$^2$, or about 42% of the sky. Therefore the total volume studied is approximately $0.55\pi d^3$.

Using the distance estimates derived above and the method of Stepien, et al. (2001), a curve was fit to the cumulative number of contact binaries detected as a function of distance, using only objects from 150 to 300 parsecs. This is a distance range in which we expect uniform completeness. As can be seen in Figure 13, the curve $N = (9.9 \pm 3.7) \times 10^{-6} d^3$ gave a good fit over this distance range. This implies a measured space density of about $(5.7 \pm 2.1) \times 10^{-6} \text{pcs}^{-3}$. However, the catalog is only about 34% complete for objects brighter than 12.5 magnitudes, which correspond approximately to those objects that are closer than 300 pcs, and thus used to determine the space density. Adjusting for this incompleteness yields a space density of $(1.7 \pm 0.6) \times 10^{-5} \text{pcs}^{-3}$. This agrees well with the recent estimate by Rucinski (2002), which was $(1.02 \pm 0.24) \times 10^{-5} \text{pcs}^{-3}$, or about 1/500 main-sequence stars in the solar neighborhood.
7. OVERVIEW OF ROTSE-III SKY PATROL DATA

The ROTSE-III robotic telescopes were also used to collect optical variability data. ROTSE-III is a set of four identical telescopes placed around the world in Coonabarabran, Australia; Ft. Davis, Texas; Mt. Gamsberg, Namibia; and Bakirlitepe, Turkey. Ideally, this distribution would allow continuous observation of sources near the equator. Each telescope has a Cassegrain structure with a 450 mm f/1.8 primary mirror and a field corrector, incident on a 2048x2048 Marconi CCD. The 13.5 $\mu$m pixels subtend 3.28" for a 1.85°x1.85° field of view. A detailed description of the ROTSE-III system is given in Akerlof, et al. (2003).

ROTSE-III was designed to search for orphan optical afterglows, as well as observe GRBs in real time. It has patrolled 328 fields regularly since September 2003, covering the strip of sky with declination $|\delta| < 2.64^\circ$, galactic latitude $|b| > 30^\circ$ and ecliptic latitude $|\beta| > 10^\circ$. These fields were selected to be visible to all four telescopes, to allow calibration and referencing with the Sloan Digital Sky Survey, to avoid galactic opacity and background due to asteroids.

The observing sequence is a pair of 60s exposures, followed by a second pair of exposures 30 minutes later. Multiple pairs of images are compiled into ‘match structures’, which contain data about individual objects, as matched by position, over a series of exposures. Details of the data reduction procedure are presented in Rykoff, et al. (2005).

The data used in my variability studies is limited to two test fields, one extending from $243.533^\circ \leq Ra \leq 245.572^\circ$ and $-2.744^\circ \leq Dec \leq -0.780^\circ$ and the other from $245.278^\circ \leq Ra \leq 247.387^\circ$ and $-2.740^\circ \leq Dec \leq -0.606^\circ$. These fields were selected because they contain several known GCVS variables faint enough to be detected by ROTSE-III. The images used were taken over three time periods; briefly in May 2003, as well as from March 2004 to July 2004 and from March 2005 to August 2005. They have
limiting magnitudes better than 17 and RMS position errors less than 0.3 pixels. These images were then sorted by limiting magnitude and the 100 most sensitive were combined into a match structure for each field. Typical limiting magnitudes range from $m = 17.5 - 19$. These match structures contain 25,125 and 28,686 objects, respectively, that appear in consecutive observations.

8. SELECTION OF VARIABLES IN ROTSE-III DATA

The method of extracting variables from the ROTSE-III sky patrol data is similar to that used for ROTSE-I. ‘Good’ points were defined to be those with no flags other than the ‘neighbors’ SExtractor flag, indicating that a neighboring object or bad pixels interfere with more than 10% of the object area, and the ‘blended’ flag described in Section 3.1. For both fields, $I_{\text{val}}$ was calculated for those objects in the match structure with at least 5 good pairs. Those objects with $I_{\text{val}}$ greater than $3 \sigma_{\text{lim}}$ were automatically phased, where $\sigma_{\text{lim}}$ is the standard deviation of groups of 100 objects, binned by average magnitude. Those phased objects with at least 30 good observations are accepted as potential variables. To avoid saturation, those objects with an average magnitude $< 12$ were removed, leaving 350 candidates in one field and 338 in the other.

To investigate the relative photometry, the 23 variable candidates with $I_{\text{val}} > 4$ were selected. By visual examination of their phased and unphased light curves, as well as comparison to individual and averaged light curves of neighboring objects, I found that nearly half of the objects have an increase in magnitude of about 0.1 - 0.2 between the second and third series of observations. These objects have deblending flags on most or all of their observations and many have either very long periods, 500 days or greater, or periods nearly equal to 1 or 0.5 days. This suggests that they are not truly variable and that improper deblending may account for a significant fraction of the candidate variables.
Further examination of these data is being undertaken by the ROTSE-III team to remove the instrumental signatures uncovered by this initial study.

9. CONCLUSION

In this work I describe the extraction of a new catalog of 1022 bright contact binary stars. All objects are selected from the extensive light curve database assembled in the Northern Sky Variability Survey from data taken from ROTSE-I sky patrol observations. Period, amplitude, light curve shape, and infrared colors are all used to identify contact binary candidates. This set of objects provided an adequate sample with which to study the fraction of x-ray activity in contact binaries, as is reported elsewhere. I also present a period-color-relation using $J-H$ color and estimate the space density of contact binaries to be $1.7 \pm 0.6 \times 10^{-5} \text{pcs}^{-3}$, or about 1/500 main-sequence stars, in agreement with other recent measurements. In addition, more recent data from the ROTSE-III sky patrols could be a further source of as yet unidentified contact binary stars.
This work makes use of the data from the Northern Sky Variability Survey created jointly by the Los Alamos National Laboratory and University of Michigan. The NSVS was funded by the Department of Energy, the National Aeronautics and Space Administration and the National Science Foundation.

This work also makes use of data products from the Two Micron All Sky Survey, which is a joint project of the University of Massachusetts and the Infrared Processing and Analysis Center/California Institute of Technology, funded by the National Aeronautics and Space Administration and the National Science Foundation.

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Stepien, K., 2005, astro-ph/0510464


This manuscript was prepared with the AAS \LaTeX\ macros v5.2.
Fig. 1.— The structure of a W UMa system. Each component star overflows its inner Roche lobe and an envelope of material surrounds the pair of stars. Image courtesy of http://www.boulder.swri.edu/terrell/talks/aavso2001/frame03.html
Fig. 2.— The figure on the top shows the distribution of modified Welch/Stetson variability indices for a representative subset of NSVS data. The dotted line shows a Gaussian fit to this distribution, and the solid line shows the variability cut (about seven $\sigma$) applied in forming the catalog. The bottom figure shows the distribution of the roughness parameter $R$ described in the text for the 63665 variables extracted from the NSVS light curve database. The dotted line shows a Gaussian fit to this distribution and the solid line shows the cut applied to identify short period variables.
Fig. 3.— Phased light curves for two contact binary candidates. In cases where the light curve is fully symmetric, as in the top two panels, it appears smooth and single-valued when phased with half the real period (left) or with the full period (right). In cases where the minima are not identical, as in the bottom panels, the light curve looks multi-valued and ‘rough’ when phased at half the real period (left), but smooth when phased at the real period (right). In each case, data is repeated to show two full cycles of the light curve.
Fig. 4.— Color-color plots in $m_{\text{ROTSE}} - J$, $J - H$, and $H - K$ for all NSVS variables. The final panel shows an Aitoff projection of all objects.
Fig. 5.— Color-color plots in $m_{\text{ROTSE}} - J$, $J - H$, and $H - K$ for those NSVS variables identified as potential short period variables by their light curve roughness. The final panel shows an Aitoff projection of all objects. It is clear from comparison to Figure 4 that the short period variables are drawn primarily from the blue population of stars.
Fig. 6.— Period-color relation for the full short period variable sample (dots). A clear sequence of objects with the period-color dependence expected for contact binary stars stands out. All stars falling within the selection region shown were selected as contact binary candidates. The known contact binaries from the catalog of Pribulla, et al. (2003) are also included (Xs).
Fig. 7.— Examples of the automatic calculation of $V_{\text{max}}$ for a random set of eight contact binaries.
Fig. 8.— Examples of the Gaussian fit to the distribution of bootstrap re-sampled $V_{\text{max}}$ values for a sample of eight contact binaries.
Fig. 9.— Distances (pcs) from parallax for the reference set of 35 contact binaries, against the distances obtained from the period-color-luminosity relation. Also included is a reference line of slope = 1.
Fig. 10.— Distances (pcs) obtained with my period-color-luminosity relation for the reference set contact binaries, against the distances obtained with that of Rucinski, in $B-V$. Also included is a reference line of slope = 1.
Fig. 11.— Residuals in distance from the period-color-luminosity relation. The included linear fits do not seem indicative of any real trend.
Fig. 12.— Residuals in absolute magnitude from the period-color-luminosity relation. The included linear fits do not seem indicative of any real trend.
Fig. 13.— Cumulative number of systems plotted as a function of distance. The dashed curve represents the curve \( N = 9.9 \times 10^{-6}d^3 \) systems per \( pc^3 \). The fit is very good out to about 300 pc.
Table 1. Properties of sample objects in the contact binary catalog \(^a\)

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\(^a\)Ra and Dec information are taken from the corresponding 2MASS observations, due to the better spacial resolution. m\(_R\) is the apparent ROTSE magnitude and \(\Gamma\) is given in days.
Table 2. Properties of sample objects in the contact binary catalog (continued) \(^a\)

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\(^a\)Max is the average magnitude of the brightest observations and Min is the average magnitude of the dimmest. Amp is the difference between them. D is given in parsecs and Obs is the number of observations passing our loose set of cuts. Included references are to the GCVS, the Pribulla catalog and the ROTSE-I test fields.