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Variable Star Census in CoRoT "Eyes"

by

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ABSTRACT

A complete catalog of variable stars in the possible observing areas ("eyes") of the CoRoT satellite is presented. All known data sources were cross-correlated and compiled confirming the variability of 81 stars formerly known as suspected variables. By means of the TIFRAN program package a comprehensive variability search was carried out on the NSVS (ROTSE-I) database for the first time in these regions. This search has demonstrated the effectiveness of TIFRAN as a tool for finding and analyzing variable stars in big databases. Our catalog contains 4925 variable stars of which 1396 stars are new discoveries. Also appended is a list of 198 suspected variable stars.

Key words: *catalogs – Stars : variables: general – Surveys*

1. Introduction

COROT (COnvection, ROtation and planetary Transit) is a small space mission for asteroseismology and exoplanetary search (Baglin *et al.* 2002). In practice it is a 30 cm space telescope equipped with a 4-element mosaic CCD camera that corresponds to two $1\overset{\circ}{.}4 \times 2\overset{\circ}{.}8$ fields-of-view: one for direct imaging for asteroseismological purposes, the other one is covered by an objective prism for searching planetary transits. The mission can be operated in two ways: either it observes a selected field for ≈ 150 days (long run), or for ≈ 30 days (short run). Annually, it is planned to have two runs of each type. The telescope can be pointed to two 10 degree radius circles around positions $\alpha = 6^{\rm h}50^{\rm m}$, $\delta = 0°0'$ ("galactic anticenter" or "winter" field) and $\alpha = 18^{\rm h}50^{\rm m}$, $\delta = 0°0'$ ("galactic center" or "summer" field). These are the CoRoT's "eyes". The satellite was launched on 27 December 2006 and it is planned to work at least until 2009. Detailed and continuously updated information about the project can be found on its main website *http://smsc.cnes.fr/COROT/index.htm*

The potential targets of CoRoT asteroseismology have been extensively studied by international collaboration and the results were uploaded to the GAUDI

(Ground-based Asteroseismology Uniform Database Interface, see Solano *et al.* 2006) but the exoplanetary areas were neglected – leastwise from the viewpoint of variable star research. The Berlin Exoplanet Search Telescope (BEST), a small aperture, wide-field telescope, is dedicated to photometric transits of exoplanets (Rauer *et al.* 2004) and will perform variability characterization of the target fields of the CoRoT mission, but no results have been published.

CoRoT's exoplanetary search is aimed at obtaining light curves from tens of thousands of stars between ≈ 12 mag and 16 mag range with millimag accuracy and uninterrupted uniform sampling within 150 (or 30) days. These data will be unique in variable star research. Our main motivation was to collect present information of the variable star content of these areas to help in planning observations by the satellite or related ground based ones.

In the course of data collecting, it turned out that in the case of the NSVS (Northern Sky Variability Survey from the ROTSE-I survey) database there had been no comprehensive variability search. As is described in Section 2 our search resulted in 1396 new variable stars.

2. Variability Search in the NSVS Database

The NSVS database is constructed from observations taken from the first-generation Robotic Optical Transient Search Experiment (ROTSE-I). The ROTSE-I telescope was originally designed to find optical counterparts to gamma-ray bursters. While waiting for a trigger from a gamma-ray burster, the telescope was set to patrol mode, which scanned the sky. The NSVS is based on a year's worth of observations from 1999 to 2000. The equipment was composed of four 20 cm $f/1.8$ telephoto lenses each equipped with 2×2 CCD mosaic cameras within $2\mathrm{k}\times2\mathrm{k}$ chips (Kehoe *et al.* 2001). This set up gave a $14\farcs4$ resolution corresponding to an $8\fdg2\times8\fdg2$ field-of-view for each element of the telescope system. Based on this the sky was divided into 206 fields each with an $16\fdg4\times16\fdg4$ area (see Akerlof *et al.* 2000). Every night the visible fields were observed in pairs of 80 s exposures in patrol mode. In some cases, multiple pairs of observations were taken for some fields in a single night. The telescope did not have a filter installed so the sensitivity of the system is similar only to that of the Cousins *R*-band.

All NSVS photometric measurements were published by Woźniak *et al.* (2004a) and are available for on-line public access from SkyDOT[1]. Akerlof *et al.* (2000) showed this sky patrol database to be a powerful resource for variable star studies. They looked over 9 sky patrol fields covering ≈ 2000 deg^2 and identified 1781 periodic variable stars. Although Woźniak *et al.* (2002) reported on an all sky variability census based on ROTSE-I data it has not been published. Only some specific types of variable stars were searched for: long period red variables (Woźniak *et al.* 2004b), Cepheids near the equator (Wils and Greaves 2004), RR Lyr stars (Wils,

[1] *http://skydot.lanl.gov/*

Lloyd and Bernhard 2006, Kinemuchi *et al.* 2006), eclipsing binaries (Otero, Wils and Dubovsky 2004). In view of this we have performed an extensive variability search in CoRoT's "eyes" to complement existing catalogs.

2.1. Preselection of Variable Star Candidates

CoRoT's eyes are overlapped by 12 sky patrol fields but only in $\approx 628\ \mathrm{deg}^2$. As a means of identifying whether or not a star in the NSVS database is a variable, a variability index (I_{var}) was used. This index is the same as that outlined in Akerlof *et al.* (2000) and Kine *et al.* (2006). They found this index to be well suited to the data distribution of ROTSE-I even though it excludes transient events such as flare stars. Such stars would be of interest not only from the viewpoint of the completeness of any variability search but also in their own right; however, in terms of data distribution, two points per night are inadequate as a means of identifying them.

A cut-off value had to be chosen for the variability index in which the star could be considered a variable star candidate. We followed Akerlof *et al.* (2000) who found $I_{\mathrm{var}} > 4.75\sigma$ to be a good criterion, where σ means standard deviation of the light curves. Those stars which have less than 11 good observed points were omitted. We extracted variable star candidates from the database with these criteria within the CoRoT eyes and obtained $\approx 82\,000$ candidates.

2.2. Selection by TiFrAn

The preselected light curves of the ROTSE-I database still represent a huge amount of data – a quantity that cannot be managed without highly automated data processing algorithms. On the other hand, the low quality and high inhomogeneity of the data were not conductive to automated methods.

False signals can be caused by many effects (random or systematic errors of the observation, trends, sampling frequency, etc.) and it is very difficult to identify them automatically because of the noisy data. For this reason, we applied a two-step semi-automated process to select the variable stars from the mass of available data.

We used TiFrAn[2] (Time-Frequency Analyzer) program package (Csubry 2002, Csubry and Kolláth 2004) a scriptable data processing tool to carry out the preliminary time-series analysis of our data. The flexible script language of TiFrAn is suitable for performing complex and repetitive tasks on large databases.

During this automated process, we calculated the frequency spectra of each light curve with standard FFT (Fast Fourier Transform) method, and found the main frequency peaks in them. The significance index of the each peak was also calculated; for this purpose the following formula was used:

$$s = (A_{\mathrm{peak}} - \langle sp \rangle)/\sigma_{\mathrm{sp}} \tag{1}$$

[2]The TiFrAn can be downloaded from *http://www.konkoly.hu/TiFrAn/index.html*

where $A_{\rm peak}$ is the amplitude of the given peak, $\langle sp\rangle$ and $\sigma_{\rm sp}$ are, respectively, the average value and the standard deviation of the frequency spectrum.

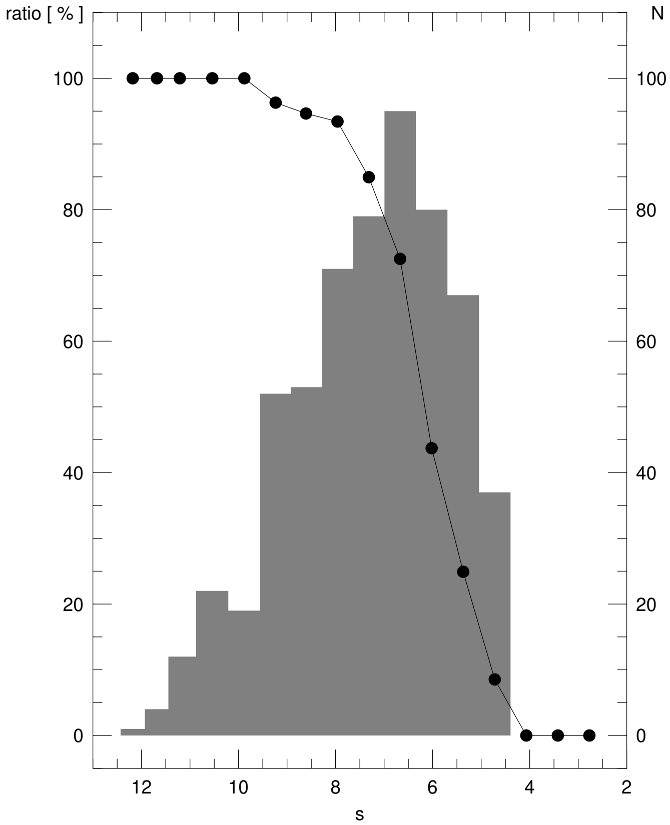

Fig. 1. Detected number (N – shaded histogram) and ratio (in per cent – line) of variable stars among preselected candidates as a function of significance index s.

We used the significance index to narrow down the group of variable star candidates. A small sample of the full database was selected and a rough manual analysis was performed on it to estimate the ratio of the variable stars among candidates with different significance indices. We found that this ratio decreases rapidly with s (see Fig. 1), and it is less than 1% if $s < 4.5$. We therefore ignored the light curves with such small s, and only the rest of the data were analyzed (4481 stars from the winter field and 5490 from the summer field: about 12% of the original data set).

Long Period Variable Stars

Before further analysis we examined the frequency distribution of the main peaks obtained in the Fourier spectra and found that a significant number of peaks have a frequency value near a whole cycle per day or zero. As Kovács, Bakos and Noyes (2005) have shown, this distribution is typical for a wide-field CCD survey and it can be assumed that most of these light curves belong to long period variable stars or otherwise they are systematic errors (trends).

To separate these two cases we tried to apply the trend filtering algorithm (TFA) elaborated by Kovács, Bakos and Noyes (2005); however, NSVS data distribution did not allow this. When constructing the template sets necessary for the TFA we need to choose a similar amount of stars as the typical number of observing points of a light curve.

Because this prevented the successful application of the method, we separated these light curves and manually examined them looking for long period variation with large amplitude. We began the visual examination at the light curves with the highest significance index. Most of these variables can be easily verified since they have quite regular and large amplitude light curves. We found 2302 such variable stars of which 1338 (58%) were not previously known. A sample is shown in Fig. 2.

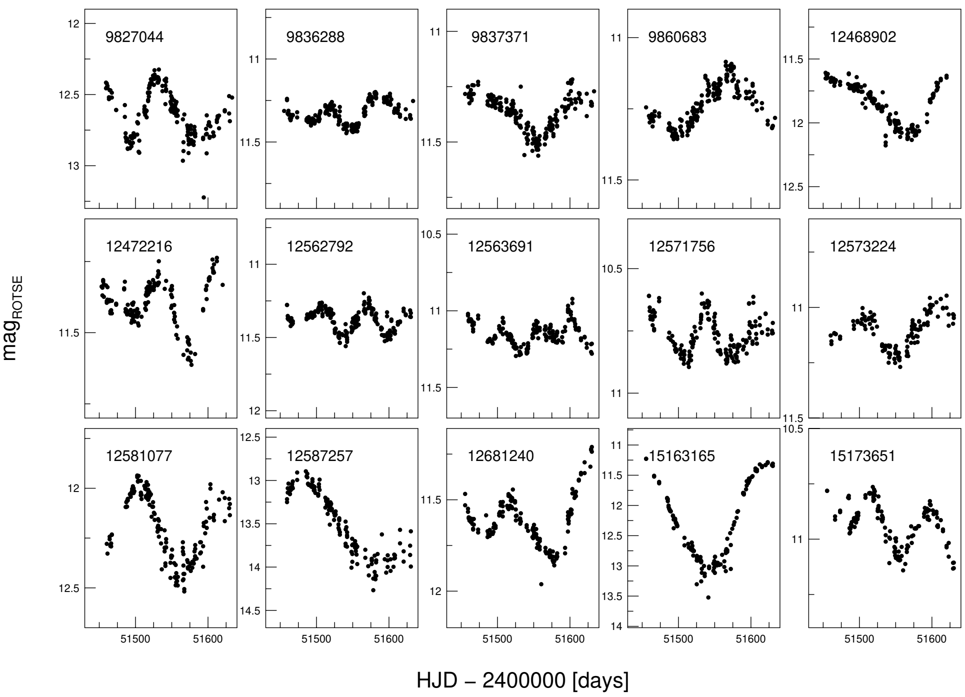

Fig. 2. Sample from the light curves of 1338 new, long period, semi-regular and irregular variable stars. The intervals between tick marks are the same for each panel.

At a lower significance index the results for semi-regular and irregular variables became somewhat obscure. The variance of the light curve may originate from observational errors or trends, and in some cases there is no way to decide. Therefore 198 of our selected stars from the low s range were handled only as variable star candidates. From these stars we prepared two separate lists, one for each direction.

The remaining light curves (with a frequency peak at zero or integer numbers, but without any sign of long-term variation) were re-processed. We performed a whitening on them to eliminate the sampling effects, and executed again the first step of our analysis. Those with significant peaks (with $s > 4.5$) were placed back into the data pool for further analysis.

Variable Stars with Shorter Period

We again used the TIFRAN program package to fulfill investigations on the remaining data. The frequency and amplitude values of the main frequency peaks were accurately calculated using linear and non-linear least squares fitting methods. Folded light curves were also generated.

We investigated the results of these calculations by eye in order to find significant evidence of the existence of periodic variation by visually exploring the original and folded light curves and the frequency spectra. With the help of this combined information, we successfully identified 206 shorter period pulsating variables and eclipsing binaries, 58 (28%) of these are new discoveries (for a sample, see Fig. 3).

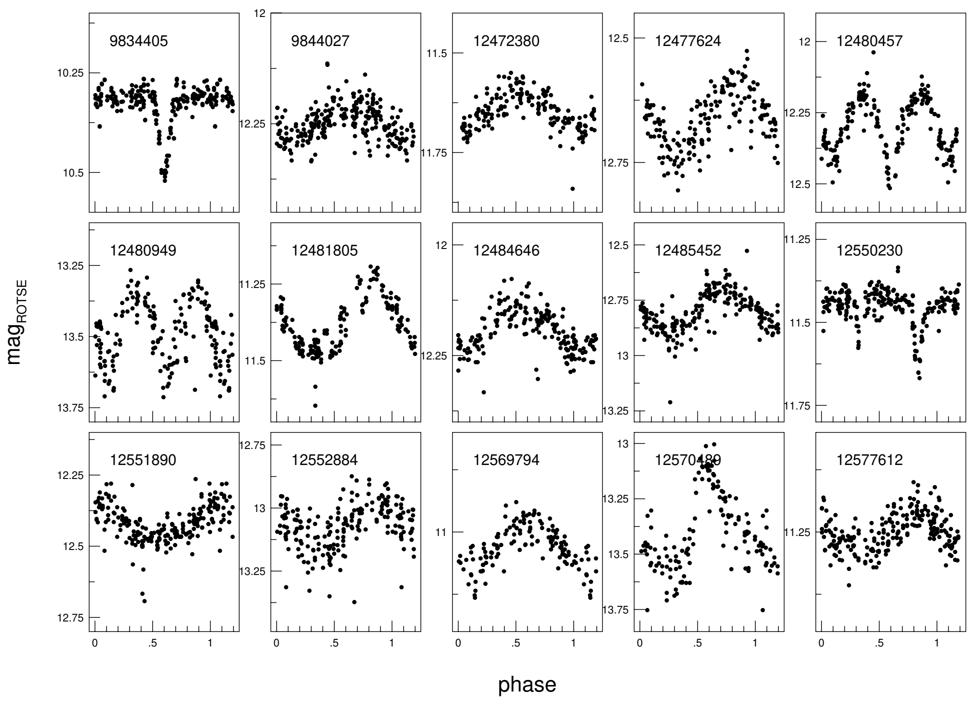

Fig. 3. Sample phase diagrams from the set of newly discovered shorter period variable stars.

2.3. Variability Classification

In accordance with Sections 2.1 and 2.2, the variable stars were divided into three groups: the group indicated by "L" means long period or not strictly periodic variables such as Miras, semi-regular or irregular variable stars, LBVs, etc.; the group with repetitive light curves and shorter periods was indicated by "S";

eclipsing binaries were indicated by "E". This last group could be separated from other variable stars because of their typical light curves. As was shown by Pojmański (2002) pulsating variables and eclipsing binaries can be well separated by the Fourier parameters of their light curves (see Fig. 5 in the cited paper).

Pojmański and Maciejewski (2004) have demonstrated that the $\log P(J-H)$ diagram, where P is the period and J, H are infrared brightnesses, is a good tool for a first guess classification of pulsating stars. With this in mind we searched for infrared colors of newly discovered variable stars in the 2MASS catalog (Skrutskie *et al.* 2006) and it allowed us a more accurate classification within group "S". Unfortunately, Mira and semi-regular type variables overlap to a considerable extent in this diagram so we decided not to split group "L" into doubtful subgroups.

2.4. Comparison with Previous Searches in NSVS

Our variability search resulted in 2490 stars in the two CoRoT areas. Of this number, 1396 were not previously known. As mentioned in the first paragraph of Section 2, some specific searches were carried out on this data. Woźniak *et al.* (2004b) published 347 long period red variable stars lying in these fields. Our pipeline missed 28 of these stars. In practically all cases this is explainable by the process having rejected all light curves with less than 11 good data points (taking the quality flag of the ROTSE-I database into account). On the other hand we found 1338 long period variable stars of which a lot are red (Mira, SR).

We found the Cepheid reported by Wils and Greaves (2004) and an additional 6 possible Cepheids were discovered. Both RR Lyr searches (Wils, Lloyd and Bernhard 2006, Kinemuchi *et al.* 2006) found no new variable stars in the monitored fields, but our process resulted in 10 candidates. Otero, Wils and Dubovsky (2004) have combined NSVS light curves with ASAS-3 (Pojmański 2002) data and found 20 new eclipsing binaries. We were able to confirm their discoveries in 15 cases on the basis of NSVS data only and we found an additional 30 eclipsing binaries.

Mention is made here that because of the large scale ($14\overset{\prime\prime}{.}4$/pixel) and astrometric transformation problems of frames the synonym problem exists in the NSVS database. The issue of multiplicity is discussed by Woźniak *et al.* (2004a). We therefore revised our table by a shell script and found some stars with multiple names even in published variable list of Woźniak *et al.* (2004b). The solution to this problem was to retain the names and positions belonging to the better light curves and delete the rest.

Here, we would say that our general search strategy was successful at least with regard to the previous studies that were tuned to special types of variable stars.

3. Catalog of Variable Stars in CoRoT "Eyes"

The main results of our study are four tables (two for each of the CoRoT directions) containing all the known and presently discovered variable stars and new suspected ones. When preparing these tables we reviewed the literature to find relevant sources. In addition to the NSVS, two large databases and a number of other publications were located and combined. These are outlined below.

3.1. Databases Used

- The electronic version of the Combined General catalog of Variable Stars[3] (GCVS 4.2, Samus' *et al.* (2004) and further references therein) includes the catalog of Variable Stars (Kholopov *et al.* 1985-1988), updated and complemented with the Name-Lists of Variable Stars Nos. 67–78. This catalog is a compilation based on a comprehensive review of the literature and complete until 2006 but none of the databases/sources referred in this Section are completely included. GCVS assigns 1573 variable stars in our fields (viz. the two CoRoT eyes).

  The Combined General catalog also contains as a separate file the upgraded New Catalog of Suspected Variable Stars (Kukarkin *et al.* 1982) and its Supplement (Kazarovets, Samus and Durlevich 1998). This catalog was cross-correlated in our tables and 58 of the suspected variable stars turned out to be real variables.

- The All Sky Automated Survey (ASAS) project dedicated to the detection and investigation of photometric variability of stars all over the sky. The first parts of this project (ASAS-1 and ASAS-2) were carried out by an automated instrument comprising a 13.5 cm telephoto lens, commercial CCD camera and an *I* filter (for details, see Pojmański 1997). Fifty selected $2^\circ \times 3^\circ$ fields were observed between 1997 and 2000 and the final catalog of variable stars was published by Pojmański (2000). Two of the selected fields, S-098 and S-110, were located in CoRoT eyes with 207 newly discovered variable stars.

  The prototype systems ASAS 1-2 were replaced by the ASAS-3 system (see Pojmański 2002). The ASAS-3 system consists of two wide-field 20 cm $f/2.8$ instruments, one narrow-field 75 cm $f/3.3$ telescope and one super-wide 5 cm $f/4$ telescope, each equipped with an Apogee $2\text{k} \times 2\text{k}$ CCD camera. The measurements were made in the *V*-band and the whole southern sky up to $+28^\circ$ declination was covered. After a comprehensive variability search the final catalog was published in five parts (Pojmański 2002, 2003, Pojmański and Maciejewski 2004, 2005, Pojmański *et al.* 2005). This is now available in electronic form as well [4]. This database has provided 1192 new items for our tables. It should be noted that even the newest electronic version of the ASAS–3 catalog does not contain all ASAS 1–2 objects.

The Flagstaff Astrometric Scanning Transit Telescope (FASTT, Stone *et al.* 1996) is an automated 20 cm meridian telescope equipped with a $2\text{k} \times 2\text{k}$ CCD.

[3] *http://www.sai.msu.ru/groups/cluster/gcvs/gcvs/*
[4] *http://archive.princeton.edu/˜asas/*

The original aim of the FASTT survey of 16 regions arranged along the celestial equator was to set up astrometric calibration for the Sloan Digital Sky Survey. As a byproduct the survey resulted in ≈ 2500 new suspected variable stars (see Henden and Stone 1998, 2000) with 8–15 total measurements per variable in the survey. We cross-correlated the position of these suspected variable stars with our catalog and found 65 corresponding items. Twenty-one variable stars are confirmed by our NSVS search result.

By pursuing the goal to find new small amplitude variables in the CoRoT eyes as a secondary target of the asteroseismology part of the mission, photometric observational campaigns have been started. The results of these campaigns are published in Bruntt *et al.* (2002), Poretti *et al.* (2003, 2005). Our catalog contains 61 small amplitude variables found by these studies.

Some other stars were taken from smaller surveys such as the Misao project (Yoshida and Kadota 1999) Berhard's own variability survey (Bernhard 2002, 2003, 2004) or Handler's list of γ Dor stars (Handler 1999).

Although numerous open clusters and associations are known in both CoRoT areas (28 in the summer and 81 in the winter field according to the newest online version of the cluster catalog of Dias *et al.* (2002)), very few of them were targeted by variable star surveys. To check in the ADS database among "center" clusters, NGC 6633 was investigated (Martín and Rodriguez 2002, Martín *et al.* 2004, Hidas *et al.* 2005); from M11 Hargis *et al.* (2005), reported 39 variables. In addition, NGC 6664, IC 4756 and Trümpler 35 are clusters in which at least one variable star member is known. In the "anti-center" area only NGC 2301 was investigated from the viewpoint of variable star research by Kim *et al.* (2001) and Howell (2005), who reported 9 and ≈ 2000 variable stars, respectively, but without positions. Thus, we could not include these stars in our catalog.

It is stressed that our catalog includes only optical and photometric variable stars. Neither spectroscopic variables without measurable photometric variability (binaries, γ Dor candidates, etc.) nor non-static radio, infrared, UV, etc. sources were added.

3.2. The Catalog

Since our tables are rather wide no sample was inserted in this paper. All tables of the catalog with a detailed description as well as the light curves of the new variable stars are available in electronic form *via*

http://www.konkoly.hu/HAG/Science/index.html

Table 1 shows the general structure of our tables, viz: table_var.center, table_var.anticenter, table_sup.center, table_sup.anticenter. If one looks at Table 1 it might seem that our catalog has a number of redundant aspects (periods, types, magnitudes from different sources); however, this information was given here as a means of expanding the tables' practicableness. As opposed to the official GCVS values, determination of the basic parameters of variable stars based upon ASAS or ROTSE

Table 1

Explanation of electronic table columns

No.	Column Name	Description
1	RA	Right ascension in decimal degrees (α_{2000})
2	DEC	Declination in decimal degrees (δ_{2000})
3–5	HH MM SS	Right ascension
6–8	±DD MM SS	Declination
9	$\mathrm{MAG_{ROTSE}}$	Averaged brightness from unfiltered ROTSE-I data
10	$\mathrm{PER_{ROTSE}}$	Period in days obtained from this study
11	$\mathrm{AMP_{ROTSE}}$	Fourier amplitude obtained from this study
12	$\mathrm{TYPE_{ROTSE}}$	Type of variable star
13	$\mathrm{I_{var}}$	Variability index
14	$\mathrm{ID_{ROTSE}}$	ID of star in ROTSE-I database
15	$\mathrm{ID_{ASAS}}$	ID of star in any of ASAS databases
16	$\mathrm{MAG_{ASAS}}$	Averaged *V* or *I* brightness given by ASAS survey
17	$\mathrm{AMP_{ASAS}}$	Total amplitude according to ASAS
18	$\mathrm{PER_{ASAS}}$	Period calculated by ASAS
19	$\mathrm{TYPE_{ASAS}}$	Variable type given by ASAS
20	VARNAME	Variable star name from GCVS or other alternative name
21	$\mathrm{MAG_{GCVS}}$	Maximum brightness from GCVS or average mag in the referred sources in Col. 24
22	$\mathrm{PER_{GCVS}}$	Period given by GCVS or source Col. 24
23	$\mathrm{TYPE_{GCVS}}$	Type from GCVS or source Col. 24
24	REF	Reference number of source

data was uniform. Since many of the stars appeared in only one of these databases we decided to give the parameters from both surveys. Furthermore, in the case of variable stars which are common in two or three databases we get an impression of the accuracy of the derived parameters.

3.3. Distribution in the Sky

If we prepare maps from the star content of our catalog (Figs. 4 and 5) it can be seen that the distribution of these variable stars is highly non-uniform in the sky (in particular towards the center). Agglomeration of stars can be explained mainly by deeper surveys (*e.g.*, ASAS 1-2, or the CoRoT team's search) but certain open clusters (*e.g.*, NGC 6633, M 11) that were previously targeted by variable star surveys also appeared. Regions with lack of stars are also due to sampling effects, wide field surveys have generally avoided crowded regions near the Galactic equator and/or could not present acceptable photometry from them (see Woźniak *et al.* 2004a, Pojmański 2002). Rectangular shape structures appearing in both maps are also caused by a similar sampling effect: they show CCD fields of surveys. From this point of view ROTSE and ASAS surveys often complement each other (compare the distribution of different symbols in Fig. 5). Therefore, if one handles the

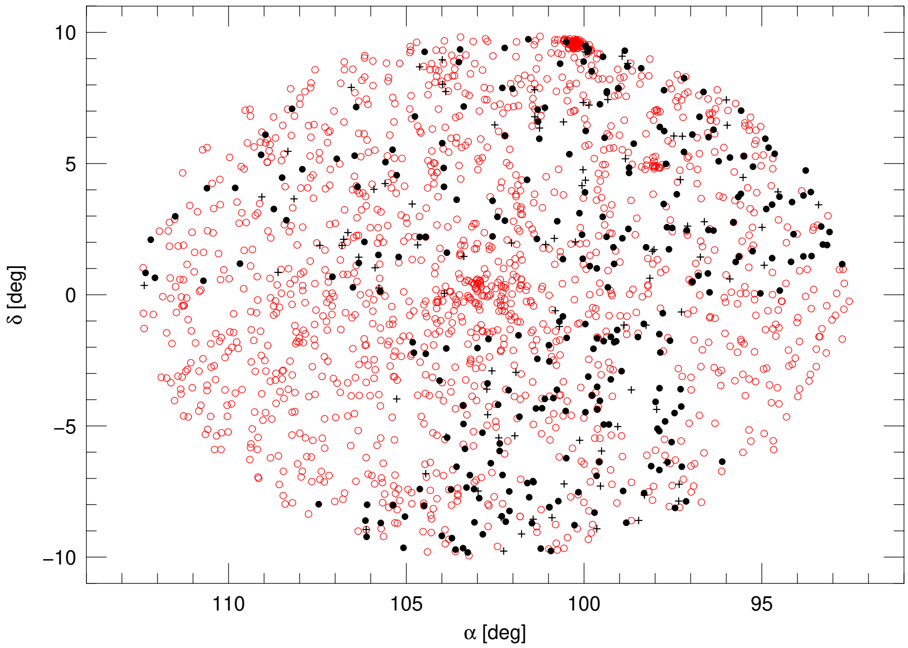

Fig. 4. Distribution of variable stars in anticenter direction. +: known variable stars discovered in NSVS database; filled circles: variables found in NSVS by the present study; open circles: known variables from all other sources.

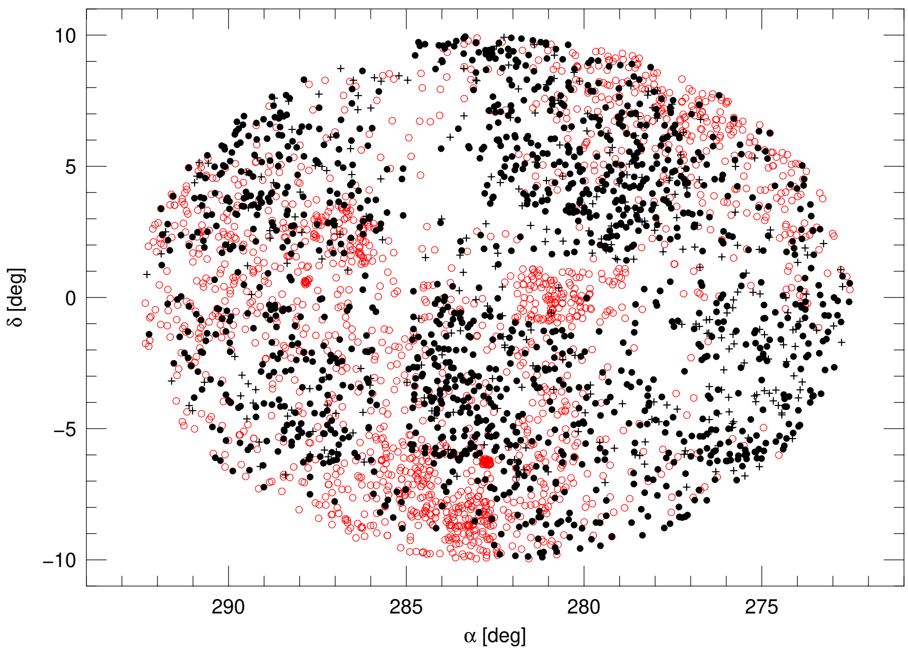

Fig. 5. Distribution of variable stars in center direction (for designations, see Fig. 4).

two (NSVS and ASAS) independent data sets together, it generally improves only the space coverage but not the time one. These factors indicate that our catalog is far from complete even in the moderate limit magnitude ($V \approx 14$ mag) of large surveys.

4. Summary

We have collected such basic parameters as position, different names, brightnesses, periods, amplitudes for all available variable stars in the two observing regions ("eyes") of the CoRoT satellite. Beyond this compilation work we carried out an extensive variable star search in the NSVS database. By using the facilities of the TiFRAN program package, we have found 1396 new variable stars and an additional 198 suspected variable stars. With the help of TiFRAN, the basic parameters, and in the shorter period cases, the types of these stars were also determined.

The positions of all former variable star lists were cross-correlated and the light curves of corresponding items were checked for correct identification. This work has revealed some multiplicity in former databases and has confirmed 81 previously suspected variable stars.

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