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# THE *CHANDRA* VARIABLE GUIDE STAR CATALOG

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## ABSTRACT

Variable stars have been identified among the optical-wavelength light curves of guide stars used for pointing control of the *Chandra* X-ray Observatory. We present a catalog of these variable stars along with their light curves and ancillary data. Variability was detected to a lower limit of 0.02 mag amplitude in the 4000–10000 Å range using the photometrically stable Aspect Camera on board the *Chandra* spacecraft. The *Chandra* Variable Guide Star Catalog (VGUIDE) contains 827 stars, of which 586 are classified as definitely variable and 241 are identified as possibly variable. Of the 586 definite variable stars, we believe 319 are new variable star identifications. Types of variables in the catalog include eclipsing binaries, pulsating stars, and rotating stars. The variability was detected during the course of normal verification of each *Chandra* pointing and results from analysis of over 75,000 guide star light curves from the *Chandra* mission. The VGUIDE catalog represents data from only about 9 years of the *Chandra* mission. Future releases of VGUIDE will include newly identified variable guide stars as the mission proceeds. An important advantage of the use of space data to identify and analyze variable stars is the relatively long observations that are available. The *Chandra* orbit allows for observations up to 2 days in length. Also, guide stars were often used multiple times for *Chandra* observations, so many of the stars in the VGUIDE catalog have multiple light curves available from various times in the mission. The catalog is presented as both online data associated with this paper and as a public Web interface. Light curves with data at the instrumental time resolution of about 2 s, overplotted with the data binned at 1 ks, can be viewed on the public Web interface and downloaded for further analysis. VGUIDE is a unique project using data collected during the mission that would otherwise be ignored. The stars available for use as *Chandra* guide stars are generally 6–11 mag and are commonly spectral types A and later. Due to the selection of guide stars entirely for positional convenience, this catalog avoids the possible bias of searching for variability in objects where it is to be expected. Statistics of variability compared to spectral type indicate the expected dominance of A–F stars as pulsators. Eclipsing binaries are consistently 20%–30% of the detected variables across all spectral types.

*Key words:* catalogs – methods: observational – space vehicles: instruments – stars: statistics – stars: variables: general

*Online-only material:* color figure, machine-readable table

## 1. INTRODUCTION

The number of known and suspected variable stars has increased tremendously in the last few decades. Between the 1940s and 1990s, the Soviet Union (later Russia) was responsible for maintaining and publishing lists of variable stars. During this time, the General Catalog of Variable Stars (GCVS) was published with some regularity (Samus 2006). The volumes contained primarily well-studied variables detected with focused programs concerning specific types of stars and specific environments. Recently, automated sky surveys have exponentially increased the numbers of known or suspected variable stars (Woźniak et al. 2004; Pojmanski et al. 2006; Damerdji et al. 2007). These automated surveys remove the bias of surveying that only included selected stellar types or environments. They primarily use small aperture telescopes with large-pixel CCDs, having relatively poor astrometric positions and photometric quality due to blending in crowded fields. The identification of the type of variability is usually an automated process and less reliable than variables that have long-term studies.

The new surveys are producing thousands of new variables, often with well-sampled light curves. Catalogs of these stars are generally being kept at the respective home institutions, and announced through publication. A new database has been created by the American Association of Variable Star Observers (AAVSO) to provide a single searchable database of these new variable stars until such time as they are added to the GCVS. Called the Variable Star Index (VSX; Watson 2006), it currently contains approximately 200,000 variable stars culled from the literature and is continuously expanding. This is the major source for confirming new variable star discoveries and for cross-checking a new catalog against known objects.

A new opportunity for variable star detection has become available with the advent of space astronomy. Pointing control of astronomical spacecraft is achieved by tracking a set of fairly bright stars with very well known positions. However, few spacecraft systems transmit guide star photometry or imagery to the ground. *Hubble Space Telescope* (*HST*) is a notable exception. A group of 4500 data sets from the available *HST* guide star data were analyzed using time series analysis (Zwintz et al. 2000). In that data set, 20 stars were found to be variable. The *HST* guide star light curves tend to be shorter in time per observation than the *Chandra* guide star light curves due to the

*HST* orbit. *HST* light curves are of high quality down to at least 11th mag and a continuation of the program started by Zwintz et al. (2000) would be of great interest. We believe there may be a wealth of as-yet undetected variable stars in the archives of some pointed space missions, if their star trackers produced a photometric signal for the guide stars.

Several space missions have stellar photometry as their primary science goal, providing high photometric accuracy to support searches for exoplanets, micro-variability, and low-level pulsations. These data sets will provide many new variable star detections. Examples of such missions are the *Wide-field Infrared Explorer* (*WIRE*) (Bruntt & Buzasi 2006), MOST (Walker et al. 2003), *Hipparcos*/Tycho (van Leeuwen 1997), *CoRot* (Baglin et al. 2009), *Kepler* (Koch et al. 2010).

Here we present the *Chandra* Variable Guide Star Catalog (VGUIDE), the most extensive catalog to date of variable stars identified from a spacecraft pointing control system. The public Web interface for this catalog is available at http://cxc.harvard.edu/vguide/. As part of the Validation and Verification (V&V) of each observation taken with the *Chandra* X-ray Observatory, the optical light curve of each of the five guide stars tracked during the observation has been examined manually. Guide stars for *Chandra* are chosen from the *AXAF*[5] Guide and Acquisition Star Catalog (AGASC), which explicitly excludes known variables of sufficient amplitude to compromise the pointing accuracy. Therefore it came as a surprise early in the mission when a number of these guide stars were identified as variables from the light curves generated by the star tracker (Cameron et al. 2002). We have now collected the stars that are clearly variable into a catalog, along with the binned light curves from all observations that used these stars for spacecraft pointing control. The Aspect Camera on board *Chandra* has maintained a high level of photometric accuracy during the mission, which makes the catalog and the light curves intercomparable. The identifications are based on examinations of the light curves of the guide stars for observations taken between 2000 January 29 and 2009 May 17. The variability was detected by the *Chandra* V&V Team while examining the guide star light curves to evaluate the quality of the reconstructed pointing of the spacecraft. Very few of the guide stars used to maintain pointing control during *Chandra* observations showed evidence of variability (see Section 5.2).

The level of variability detectable by eye in the *Chandra* VGUIDE ranges from about 0.02–0.03 mag (peak to trough) to extreme examples of more than 0.5 mag, depending on the noise level. It is quite possible that the archives of the *Chandra* observations contain significantly more variable light curves than are cataloged here. In particular, long-term variability may not be noticed in a single observation, but might be apparent if the light curves from multiple observations are combined. Variations caused by spacecraft dither (see Section 2.3), coupled with the lack of a good noise model for the detector (see Section 4), limit our confidence in the variability detections to examples greater than 0.02 mag.

One of the important benefits of the VGUIDE Catalog is that many of the identified variable stars have been used multiple times as guide stars over the more than 10 years of the mission. Thus we have several segments of the full period that can be used for period determination and parameter calculations. We have not attempted to combine the multiple light curves for period analysis in this paper.

[5] Renamed *Chandra*.

**Table 1**
Aspect Camera Characteristics

| Characteristic | Description |
|---|---|
| Optics | Cassegrain telescope with refractor triplet |
| Focal length | 991 mm |
| Aperture | 0.11 m |
| Focal plane | TK1024 CCD |
| Pixel size | 24 $\mu$m × 24 $\mu$m |
| Nominal plate scale | 5″ pixel$^{-1}$ |
| Field of view | 1°.4 × 1°.4 |
| Normal integration time | 1.7 s |
| Magnitude limit | ∼10.6 mag |

With apparent magnitudes of 6–11, the stars in this catalog are in general nearby and easily observed with modest equipment on the ground for followup. They are also good candidates for detailed spectroscopic followup. The stars are preferentially later-type stars due to the 4000–10000 Å sensitivity of the *Chandra* Aspect Camera. The maximum duration of a single observation is 2 days, an advantage that is not available with a satellite in low Earth orbit.

The telescope specifications and details of the observations are described in Section 2. Section 3 describes the method of detection of the variable stars in VGUIDE. Light curves created for each variable star are discussed in Section 4, with the description of the downloadable files. Section 5 includes a description of the VGUIDE catalog contents and statistics of the frequency of variability in relation to spectral type and variability type. Conclusions are stated in Section 6.

## 2. OBSERVATIONS

### 2.1. *Description of Aspect Camera and Guide Star Catalog*

Pointing control during *Chandra* observations of X-ray targets is achieved with the onboard Aspect Camera Assembly (ACA) that tracks five guide stars continuously during each science observation.[6] The Aspect Camera is an 11.2 cm, $f/9$ Ritchey-Chrétien optical telescope, mounted parallel to the X-ray telescope boresight. A single 1024 × 1024 pixel Tektronix CCD is the focal plane detector. Each pixel on the ACA CCD covers 5″ × 5″. The ACA CCD has a relatively fast 1.7 s integration time. Tracking of each guide star during an observation is achieved by calculating the centroid on the star image every ∼2.05 s. Processing of the data on the ground after the observation uses both forward and backward Kalman filtering, resulting in improved pointing reconstruction (Aldcroft et al. 2000; Cameron et al. 2000). Centroiding information and raw sub-image data from the detector are available via telemetry and can be obtained from the *Chandra* archive. The characteristics of the ACA on board *Chandra* are listed in Table 1.

Figure 1 is an actual pre-flight photograph of the X-ray telescope aperture (concentric circles), with the aperture of the ACA shown as a smaller circle to the right of the X-ray telescope aperture.

All guide stars are selected from the AGASC star catalog, which is based on the *HST* Guide Star Catalog (Lasker et al. 1990) with proper motion information from the Catalog of Positions and Proper Motions (Röser & Bastian 1989) and updated positions and magnitudes from the Tycho-2 catalog (Høg et al. 2000). Of course, guide stars are selected for each

[6] See Section 5.2 of the "Proposers' Observatory Guide," http://cxc.harvard.edu/proposer/POG/html/chap5.html#tth_sEc5.2.

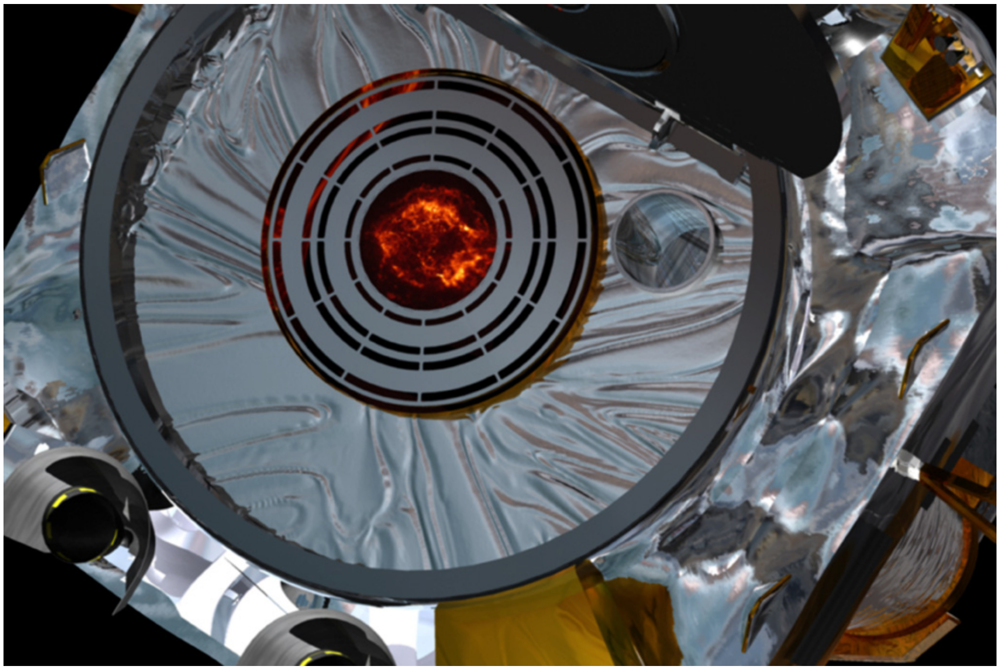

**Figure 1.** Pre-flight photograph of *Chandra* spacecraft showing position and orientation of the ACA aperture with respect to the X-ray telescope aperture. The X-ray telescope is a concentric group of grazing incidence parabolic–hyperbolic mirrors with the aperture identifiable in this photograph as a series of concentric circles. The X-ray image of the supernova remnant Cas A has been superposed in the center of these circles. The ACA aperture is directly to the right of the X-ray aperture in this image, with the ACA Stray Light Shade at the fore. Photograph courtesy of the *Chandra* X-ray Observatory Center, which is operated by the Smithsonian Astrophysical Observatory on behalf of NASA.

observation based only on positional considerations such that the stars are well dispersed throughout the field of view and not near another bright object. The only consideration is the ability of the ACA to maintain tracking of the star throughout the observation. No consideration is given to the potential variability of the selected guide stars.

### 2.2. *Aspect Camera Photometry and Calibration*

The ACA CCD has a spectral response from 4000 to 10000 Å (much broader and redder than the Johnson *UBV* filters). The Aspect Camera flux calibration is referenced to a zero magnitude star of spectral type G0 V. Based on flight data, the conversion from $V$ and $B$ magnitudes to the instrumental magnitude is approximately

$$m(\mathrm{ACA}) = V + 0.426 - 1.06(B - V) + 0.617(B - V)^2 - 0.307(B - V)^3.$$

A star with an ACA magnitude of 10.32 produces about 5263 $e^{-}\mathrm{s}^{-1}$ and has a noise of about 300 $e^{-}\mathrm{s}^{-1}$. The values of $\mathrm{m}_{\mathrm{ACA}}$ are sixth to eleventh mag. Calibration of the secular trends of the ACA response is based on repeat observations of a set of standard guide stars. Results from the first several years of the *Chandra* mission show that the change in average star magnitude was less than 0.002 per year. Repeated calibrations indicate that this trend has not changed significantly in subsequent years. Better than 1% relative photometry is believed possible with the ACA. A full description of the on-orbit performance of the ACA can be found in Weisskopf et al. (2003).

Measured star magnitudes may occasionally be affected by CCD dark current, cosmic rays, or by "warm" pixels. Warm pixels have a high level of residual charge and can produce an artificial bright spot on a guide star image. Cosmic rays can brighten the image for a single readout, but rarely have any lingering effects. In order to minimize dark current, the CCD is cooled to $-19^{\circ}$C ($-10^{\circ}$C and $-15^{\circ}$C earlier in the mission). ACA dark current calibration measurements have been made every three or four months throughout the *Chandra* mission and have shown the typical trends due to accumulated CCD radiation exposure and changes in the CCD temperature set point.

### 2.3. *Spacecraft Dithering*

For most observations with *Chandra*, the spacecraft is commanded to "dither" in pointing attitude such that the pointing follows a system of parametric equations mapping a two-dimensional harmonic motion (known as a Lissajous pattern) with angular extent typically $\sim 20''$ (see Figure 2). This dithering is implemented to average the signal inhomogeneities in the X-ray detectors and minimize the potential of damage to the detectors. As guide stars shift position on the CCD due to the dither pattern, one or more of them may periodically pass over warm CCD pixels, causing the guide star image to brighten. This produces low-amplitude, relatively high-frequency (700 s or 1000 s period) magnitude variations that are visible in many guide star light curves.

## 3. DETECTION METHOD

The light curve for each guide star used in a *Chandra* pointing is quantitatively evaluated to determine how well the star was tracked by the ACA. The examination of the guide star light curves is done by the *Chandra* V&V Team (J.N., D.H., J.L., and B.S.), usually within 24 hr of the observation. This V&V process is a standard operating procedure for the *Chandra* mission and tools for viewing the light curves are provided by the *Chandra* Data Systems (Deponte Evans et al. 2006). The goal of the V&V process is to verify that the observation was performed according

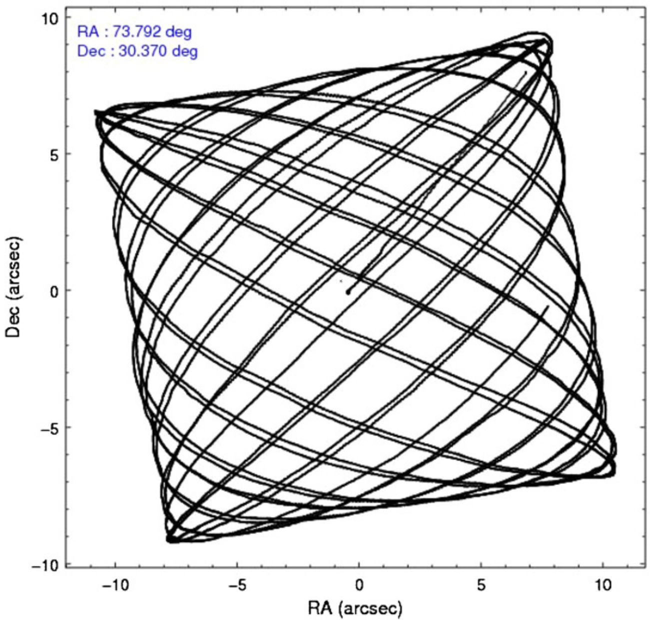


**Figure 2.** Example of dither pattern of *Chandra* pointing during a 15 ks observation. The *x*- and *y*-axes are the offsets of the optical axis from its mean pointing.

(A color version of this figure is available in the online journal.)

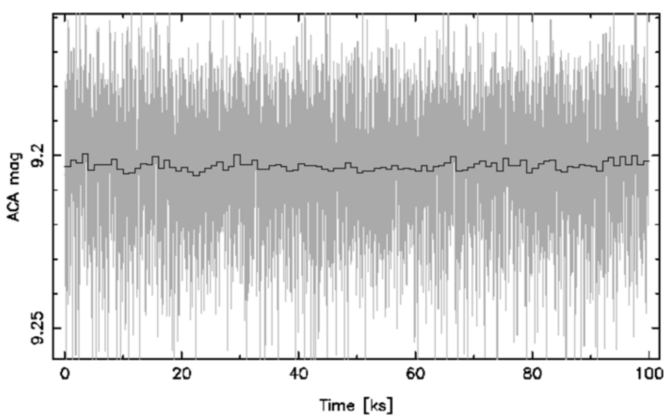


**Figure 3.** Example of a *Chandra* guide star light curve that is not considered variable in this catalog. The gray lines represent the actual data at the instrument resolution. The black line represents a 1 ks binning of the data. Noise level is typical.

to observer specifications and engineering requirements, and that the data reduction was done correctly. In the course of examining light curves to evaluate the quality of the guide star tracking, the V&V Team noticed that some light curves had the signatures of well-known stellar variability classes. The variability detected did not interfere with the successful tracking of the star by the Aspect Camera and did not cause the spacecraft to lose track or endanger the mission. A database was constructed to log the variable star discoveries and record information from SIMBAD, VSX, and other external sources.

Figure 3 is an example of a *Chandra* guide star light curve that shows no variability. Figure 4 is an example of a guide star light curve that shows periodic variability due to a warm pixel encountered during the dither cycle. Figures 5 and 6 are examples of light curves we identified as variables.

There have been more than 75,000 light curves of guide stars created during the *Chandra* mission. Each has been examined for variability. These light curves represent more than 37,000 unique objects. Variability has been detected in 827 unique objects, representing about 2.25% of the guide stars used by *Chandra* for pointing control during this period.

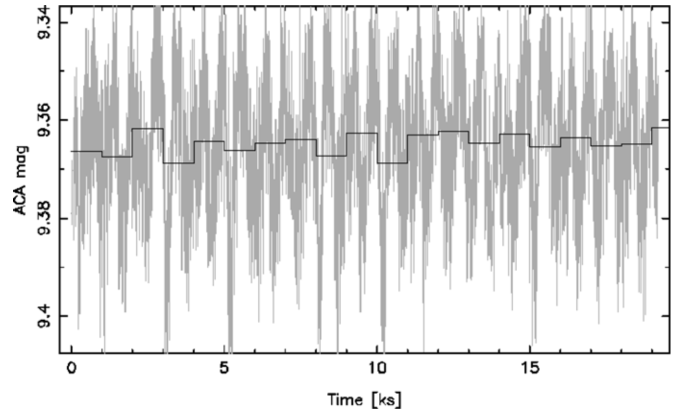


**Figure 4.** Example of a *Chandra* guide star light curve that shows evidence of magnitude fluctuations related to the spacecraft dither pattern. The gray lines represent the actual data at the instrument resolution. The black line represents a 1 ks binning of the data. This star is not considered variable in this catalog. Variations with a period of approximately 1 ks are seen, which correspond to the dither period.

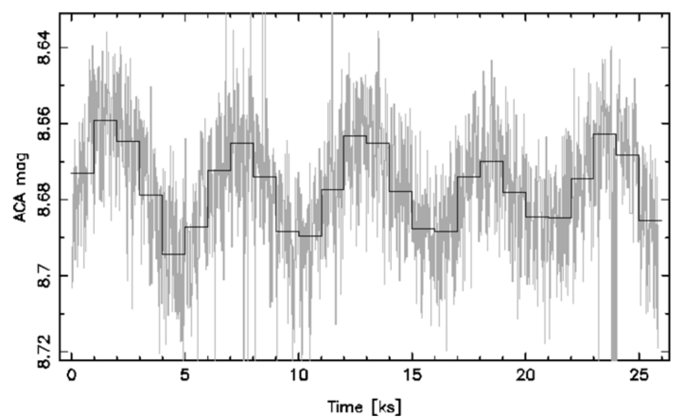


**Figure 5.** Example of a *Chandra* guide star light curve that shows evidence of pulsational variability. The gray lines represent the actual data at the instrument resolution. The black line represents a 1 ks binning of the data. Noise level is typical.

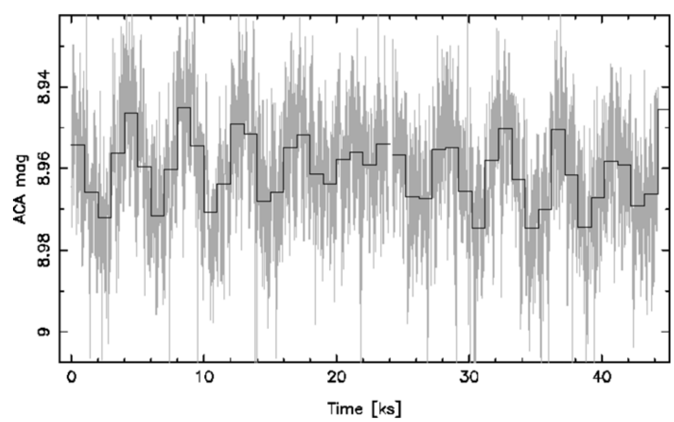


**Figure 6.** Example of a *Chandra* guide star light curve that shows evidence of pulsational variability. The gray lines represent the actual data at the instrument resolution. The black line represents a 1 ks binning of the data. Noise level is typical.

**Table 2**
Light Curve FITS Header Keywords[a]

| Keyword | Value | Description |
|---|---|---|
| EXTNAME | Light curve | Identifies the type of data tabulated |
| CONTENT | Light curve | Defines the type of data tabulated |
| MJDREF | 50814 | Modified Julian Date reference for *Chandra* data |
| DATE_OBS | *(2000-01-17T14:09:39)* | The date and time the observation started |
| OBS_ID | *(1164)* | Observation identifier |
| AGASCID | *(1200883536)* | AXAF Guide and Acquisition Star Catalog (AGASC) ID |
| TIMEZERO | *(64505379.6641316)* | Time offset of start of data, in seconds since MJDREF |
| TSTART | *(0)* | Start of observation, set to zero |
| TSTOP | *(1940.224)* | End of observation, in seconds since TSTART |
| EXPOSURE | *(1526.427)* | Exposure time; instrument integration time, in seconds |
| SLOT | *(6)* | Guide star software "slot" |
| aca_ccd_gain | 5 | ACA calibration data used |
| aca_ccd_read_noise | 25 | ACA calibration data used |
| aca_mag_0 | 10.32 | ACA calibration data used |
| aca_rate_mag_0 | 5263 | ACA calibration data used |

**Note.** [a] Example values are given in parentheses in italic.

**Table 3**
Light Curve Table Columns

| Name | Unit | Description |
|---|---|---|
| time_bin | 1 | Bin number (starting at 1) |
| JD | day | Julian Day at bin center (ASCII version only) |
| time | s | Time at bin center |
| time_min | s | Time at start of bin |
| time_max | s | Time at end of bin |
| Counts | counts | Counts, integrated over the time bin |
| stat_err | counts | Statistical error on counts |
| Exposure | s | Exposure time in the bin |
| count_rate | counts $s^{-1}$ | Mean count rate in the bin |
| count_rate_err | counts $s^{-1}$ | Statistical error on count_rate |
| Mag | ACA magnitude | Instrumental magnitude |
| mag_err | ACA magnitude | Statistical error on magnitude |

## 4. LIGHT CURVES

We have created individual light curves for each variable star detected, customizing the products to enhance further research. The light curve products we produce for the guide stars are repackaged versions of the aspect pipeline products. These "`ACACENT`" (ACA centroiding) and "`GSPROPS`" (guide star properties) files,[7] which are not routinely delivered to users as standard products, but are available in the supporting data directories as the `pcadf*_acen1.fits` and `pcad*_gspr1.fits` files, contain much information in addition to the photometry. These files cover specific time periods and several files may be required to include an entire observation. Multiple guide stars are included in each file. We have collated the relevant data for each star for each observation, scaled the counts to magnitude, and packaged into a FITS binary table. Individual light curves are also available as ASCII download from the VGUIDE Web site. The header key words for the light curve FITS files are listed in Table 2, along with their values and descriptions. Table 3 identifies the columns in the light curve tables.

These files contain all the information relevant for visualization or analysis of the light curves on a per-star, per-observation basis. We provide the default tables at the full time resolution of the Aspect Camera, which is 2.05 s. This should not, however, be interpreted as the exposure time per sample—there is dead time in the camera such that the exposure is about 1.7 s per frame. There are also occasionally bad CCD frames for which there is zero exposure. For this reason, and for purposes of rebinning light curves, we also include the exposure per bin; this is set to zero for bad frames. It must be realized that the fundamental signal is the counts integrated over a frame. That is, the light curve is a histogram-type quantity. Hence, we tabulate the minimum and maximum time bin values in the file.

Bad data are sometimes unavoidable and cannot always be eliminated by setting the frame's exposure to zero. Cosmic rays can create temporarily warm or flickering pixels on the CCD, and as the aspect dither moves the star image over such a region, the count rate is affected. The static bad pixels are removed by the fitting algorithm, but the transient ones remain and can sometimes be seen as spikes in the light curve, or as features modulated at the period of the spacecraft dither (about 700 or 1000 s). Rebinning at the dither period is a simple way to suppress these artifacts.

Statistical errors based on the counts are tabulated in the files, but they are approximate. The aspect pipeline does not record an uncertainty on the fitted counts. We estimate the uncertainties from the aspect camera CCD calibration information, which also requires a number of pixels to include the read noise. Flickering and warm pixels can dominate the noise, so the data variance tends to be larger than our statistical uncertainty. For reference, the FITS file headers contain the assumed CCD calibration parameters.

In Figure 7, we show an example light curve at full time resolution and rebinned to 1000 s intervals. The dropouts to large magnitude (fainter) are bad frames. The upward spikes are either statistical noise or warm/flickering pixels. A curve rebinned to 1000 s intervals is overplotted and shows suppression of artifacts. Each curve's tabulated times start at $t = 0$, and the absolute offset is given by the `TIMEZERO` and `MJDREF` (reference for Modified Julian Date) values in the header. Rebinning is done by interpolating exposures onto a new time grid, then performing an exposure-weighted sum of rates from the original grid to the new grid. That is, we integrate the counts per bin onto the new time grid and interpolate where necessary to account for fractional bin overlap, then divide by the new exposure for each bin to determine the new rate. This properly accounts for missing data as flagged by zero-exposure bins, but not for transient warm pixels. We have used a uniform time grid, though this is not strictly necessary. It is definite that exposures

[7] See Section 5.9.1 of the "Proposers' Observatory Guide" (POG), http://cxc.harvard.edu/proposer/POG/html/chap5.html#tth_sEc5.9.1.

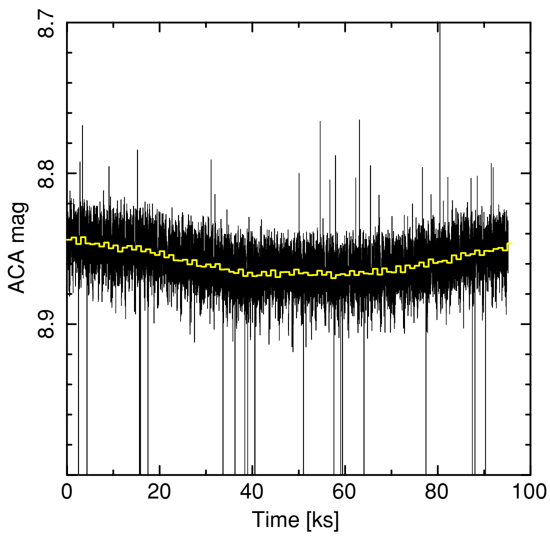


**Figure 7.** Example light curve for star 667683800 from observation ID 7457. The black curve is at full time resolution (2.05 s), and the overplotted curve is rebinned to 1000 s. Downward spikes are missing frames. Upward spikes are statistical fluctuations or due to warm and flickering pixels. The star shows sinusoidal variability with an amplitude of about 0.02 mag at a period of about 100 ks (1.16 days).

per bin are not constant. We have not investigated methods that may further reduce systematic noise, such as median filtering, iterative clipping of high values, or Fourier filtering of features at the dither period; these are all possible candidates for improving the quality of some of the light curves.

FITS files downloaded from the VGUIDE Web site have times referenced to MJDREF because that is the time standard used by the *Chandra* Project and the input files used to create the light curves use MJDREF. The ASCII download files are derived from the FITS files, but have both MJDREF and JDREF (reference for Julian Date) in the header information and include a column of data with Julian Date (JD) time for each time bin.

## 5. DESCRIPTION OF THE *CHANDRA* VGUIDE CATALOG

The VGUIDE catalog consists of a list of all *Chandra* guide stars classified as variable or potentially variable by us during the period 2000 January 29 to 2009 May 17. Additional information collected from SIMBAD and VSX is included; the SIMBAD and VSX information is current as of 2009 May 17. In addition to the online presentation of the data from the *Chandra* VGUIDE available with this publication, the catalog is available publicly at http://cxc.harvard.edu/vguide/. The Web interface allows the user to display a listing of all the variable stars with mouse-hovering visibility of one of the available light curves for that star, capability of sorting the list of stars on any columns, and links to SIMBAD. The user can select which columns to display interactively. Also, a detail page is available for each star on the public Web site that shows all the data particular to the star, including a light curve for each individual *Chandra* pointing. Light curves of every variable star detected in *Chandra* guide star data for each observation that used the guide star are available for download from the public Web interface. The light curves can be downloaded as either ASCII files or FITS files. In an explanatory file provided with each FITS download of a light curve, header keywords and typical values relevant to the light curve are provided, as well as the FITS table columns. The ASCII files are self-documented.

The Web-based version of the VGUIDE catalog consists of a PHP: Hypertext Preprocessor and Cascading Style Sheets-based interface with a MySQL database back end. Some javascript is included to add some features but it is not required for the Web site to work. The sources of information for the database include the *Chandra* Guide Star Catalog (AGASC), SIMBAD, VSX, some literature searches, and analysis by the authors. Based on the review of these sources and our own analyses, a status is assigned to each potential variable star of ACCEPTED or SUSPECT. Published variability categories were recorded if available. For previously unknown variables, we assigned variability categories if the data were sufficient to justify a categorization (see Section 5.1).

Table 4 defines the available columns of information in the VGUIDE catalog. The full catalog is available online with this publication. Information available on each star detail Web site is not presented as an online table because of the complexity of multiple observations and download capability built into these pages.

This release of the VGUIDE catalog includes variable guide stars identified in *Chandra* pointing data for the period 2000 January 29–2009 May 17. Future releases of the VGUIDE catalog will include more recent data as well as variable guide stars from the immediate post-launch period 1999 August–2000 January. Examples of variable guide stars in the VGUIDE catalog are shown in Figures 8–11.

### *5.1. Classification*

The categories and classifications were determined for each star in one of two ways. If the star was a previously known variable and had an entry in the VSX database, the category and classification were taken directly from VSX. If the star was not a previously known variable, the authors used the full set of *Chandra* guide star data for that star to make a classification. A column in the VGUIDE catalog indicates whether a star is a previously known variable, differentiating the source of the classification.

VSX is not, in general, a primary source for variable star information. It is a compendium of information from many sources, including SIMBAD, GCVS, publications concerning individual stars or groups of stars, and archives at various observatories. We have not researched each known variable in the VGUIDE to verify VSX information or to obtain the primary reference. Nor have we attempted to evaluate whether the newly reported *Chandra* guide star data reported here support previous classifications. In addition, VSX is a live database that is continually updated. The information in VGUIDE is a snapshot of the VSX data in late 2009. Since that time, several of the stars that we report as previously unknown may have appeared in VSX. Classifications may have been updated. We used the VSX data in order to do statistical evaluation of the VGUIDE stars. Investigators interested in particular stars in VGUIDE should get updated information from VSX and do a thorough literature search for the stars of interest. Not all VSX stars have a variable category and classification, and only a few have epoch and period. We have entered all information available in VSX for these fields.

The authors have classified all the VGUIDE stars that were previously unknown variables. The classification was done by visual examination of all of the guide star data available from *Chandra* for each star. The specific criteria used for this classification are described below. We did not do a frequency or period-folding analysis on the data, which would lead to

**Table 4**
The VGUIDE Catalog

| Column Heading | Source | Description |
|---|---|---|
| AGASCID | AGASC | Unique numerical identifier assigned to guide star |
| SIMBAD name | SIMBAD | Star name as defined by SIMBAD |
| R.A. | AGASC | Right ascension in sexagesimal units |
| R.A. (deg) | AGASC | Right ascension in degrees |
| Decl. | AGASC | Declination in sexagesimal units |
| Decl. (deg) | AGASC | Declination in degrees |
| SIMBAD long type | SIMBAD | Type of star in English text |
| SIMBAD spectral type | SIMBAD | Spectral type of star |
| SIMBAD type | SIMBAD | Type of star in shorthand text/symbols |
| Category | VSX, others | General variable category |
| GCVS classification | VSX, others | Classification of variability |
| Epoch | VSX | Epoch |
| Period | VSX | Period of variability |
| UV source | SIMBAD | Yes/no UV source |
| X-ray source | SIMBAD | Yes/no X-ray source |
| IR source | SIMBAD | Yes/no IR source |
| No. of obs. | *Chandra* archive | Number of *Chandra* observations using this star |
| Total obs. time | Calculated | Total *Chandra* observing time using this star |
| Known variable | VSX | Y/N |
| Status | This paper | ACCEPTED/SUSPECT |

**Note.** Shown here is the description of the columns in the VGUIDE Catalog. The full catalog data is available as a machine-readable table in the electronic edition of the journal
(This table is available in its entirety in a machine-readable form in the online journal. A portion is shown here for guidance regarding its form and content.)

**Table 5**
VGUIDE Stars with At Least 1000 ks Total Exposure Time

| AGASC No. | SIMBAD Name | *V* mag | Spec Type | Category | Classification | No. of Observations | Total Exp. Time (ks) | Known Variable | Status |
|---|---|---|---|---|---|---|---|---|---|
| 845807880 | CD-28 1189 | 8.80 | K5 | Indeterminate | | 30 | 2831 | N | ACCEPTED |
| 845676728 | HD 21968 | 9.53 | K2III | Indeterminate | | 30 | 2699 | N | ACCEPTED |
| 1201410616 | HD 37121 | 9.16 | F2V | | | 62 | 1989 | N | SUSPECT |
| 525732232 | HD 240299 | 9.07 | F8V | | | 59 | 1887 | N | SUSPECT |
| 1200885760 | HD 269788 | 9.93 | K4III | | | 61 | 1521 | N | SUSPECT |
| 1130643264 | V* V429 Car | 6.42 | WNv+... | Eclipsing | EA/WR | 45 | 1474 | Y | ACCEPTED |
| 1130632200 | HD 93403 | 7.30 | O6e | Indeterminate | IA | 44 | 1445 | N | ACCEPTED |
| 525732528 | HD 220832 | 9.07 | A4V | | | 69 | 1434 | N | ACCEPTED |
| 912275088 | HD 208662 | 8.98 | G1V | | | 73 | 1429 | N | SUSPECT |
| 896403224 | HD 160665 | 8.04 | F2V | Indeterminate | | 53 | 1366 | N | ACCEPTED |
| 505809632 | HD 126138 | 7.59 | B9V | Pulsating | | 43 | 1357 | N | ACCEPTED |
| 525735976 | V* V811 Cas | 8.62 | B0.5Vpe | Pulsating | BE | 78 | 1319 | Y | ACCEPTED |
| 114955056 | HD 109032 | 8.08 | F0 | Indeterminate | | 91 | 1244 | Y | ACCEPTED |
| 440149808 | V* IM Aur | 8.11 | B7V | Eclipsing | EA | 42 | 1121 | Y | ACCEPTED |
| 898247688 | HD 162742 | 8.45 | B4Ib/II | Pulsating | BCEP | 23 | 1088 | N | ACCEPTED |
| 967053960 | HD 162512 | 9.02 | F0V | Pulsating | | 17 | 1032 | N | ACCEPTED |
| 114950584 | BD+12 2480 | 9.60 | M0 | Indeterminate | | 78 | 1027 | N | ACCEPTED |

potentially more accurate classifications. Data from ground-based observatories were not considered in this classification effort. By definition, there is no information in SIMBAD concerning the variability of these previously unknown variables, because VSX would contain an entry for a SIMBAD-identified variable. The authors' classifications should be considered preliminary because additional data from other instruments may alter the classification. However, this paper should be considered the primary reference for the classification of these previously unknown variables. The categories and classifications follow the GCVS guidelines.

Most of the previously unknown variable stars in VGUIDE were classified as pulsators by the authors. We note that while many of these stars are clearly pulsating, with multiple modes of pulsation, it is often difficult to differentiate pulsators from rotating or spotted stars. We assigned the category of pulsating and the classification of $\delta$ Scuti (DSCT) and low-amplitude $\delta$ Scuti (DSCTC) to non-sinusoidal variations with a clear period or periods. Evidence of multiple pulsation modes of a few hours or less was quite common in the light curves. The amplitude of the variations most commonly seen was 0.02–0.04 mag, so our classification was DSCTC for these low amplitude pulsators, following the GCVS guidelines. In particular, the F stars show DSCT, DSCTC, and $\gamma$ Dor (GDOR) variations, the latter being early F dwarfs with multiple periods up to 1 day. GDOR variations are sinusoidal, while the DSCT variations are non-sinusoidal. If the light curve could be determined to be non-sinusoidal, a classification of

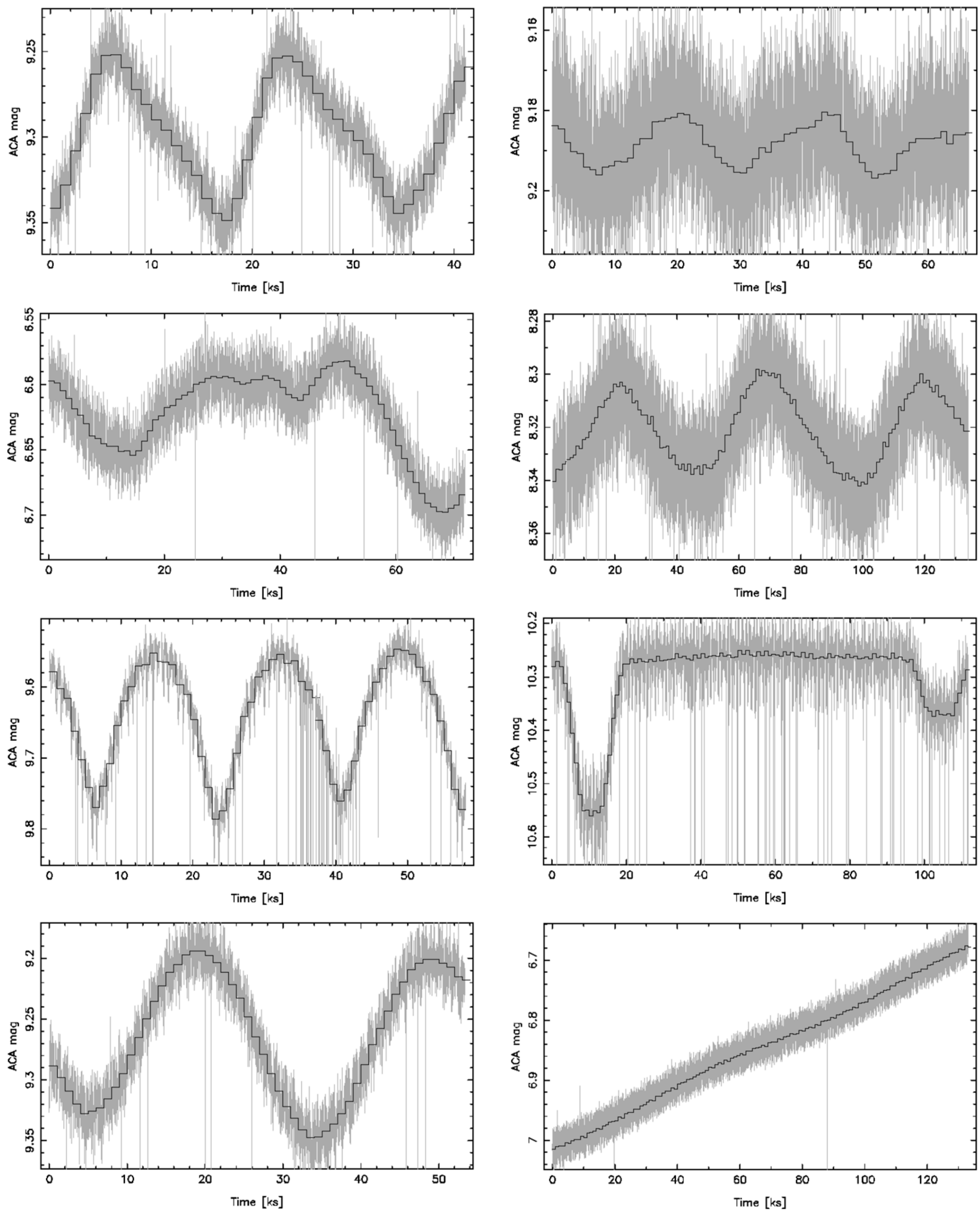


**Figure 8.** Examples of variable stars in the VGUIDE catalog. Observations are of varying lengths, as indicated on the *x*-axis. The gray lines represent the actual data at the instrument resolution. The black line represents a 1 ks binning of the data. From left to right, top to bottom: HD 152077 (AGASC_ID 1032856344), HD 68157 (1066965568), HD 77320 (1007822296), HD 109032 (114955056), BD + 21 345 (160181128), BD + 30 2254 (260965416), HD 281155 (309330608), V* ER Car (1130893464).

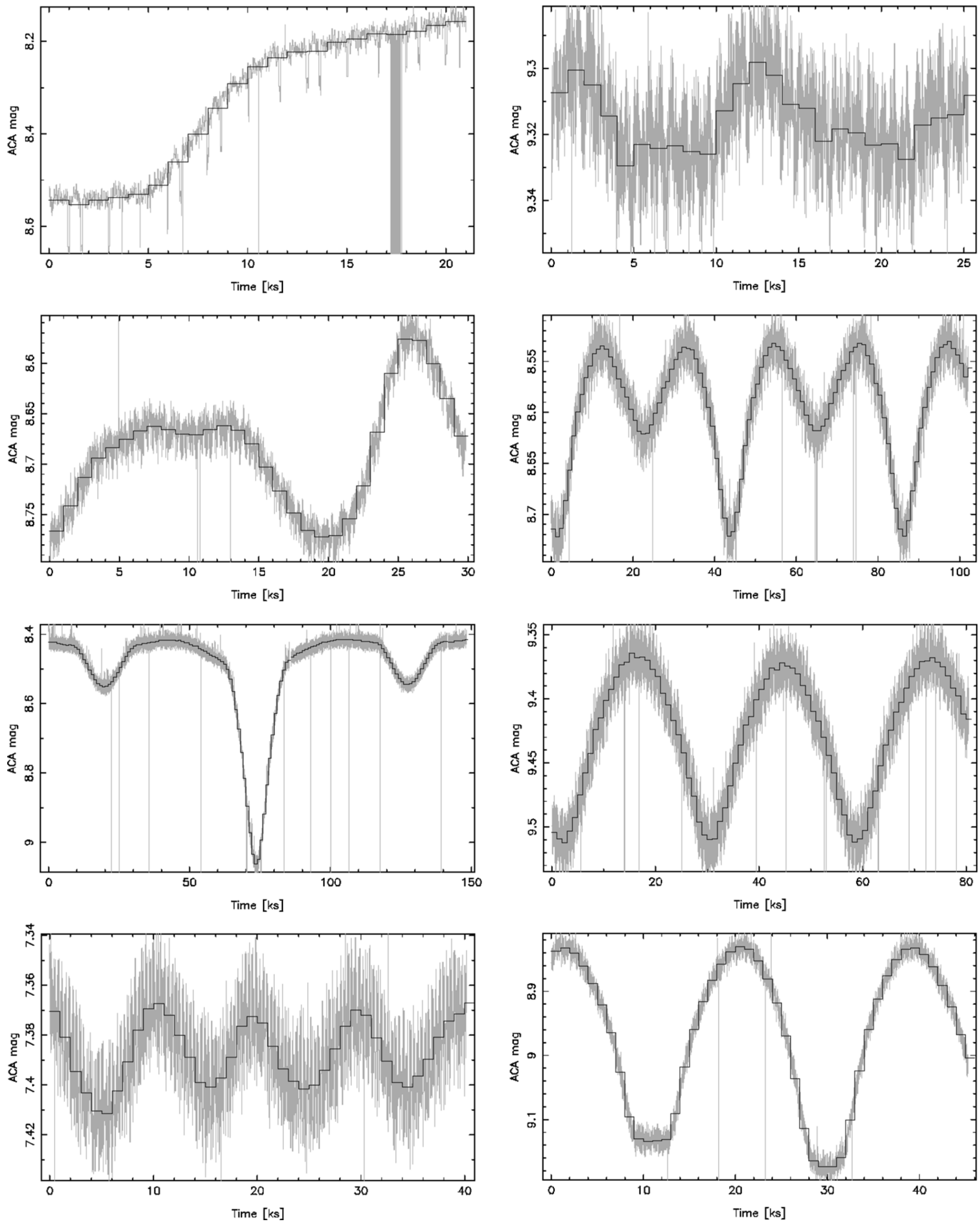


**Figure 9.** Examples of variable stars in the VGUIDE catalog. Observations are of varying lengths, as indicated on the *x*-axis. The gray lines represent the actual data at the instrument resolution. The black line represents a 1 ks binning of the data. From left to right, top to bottom: V* V459 Aur (AGASC_ID 317983984), BD + 42 3726 (414723776), HD 213616 (420100064), HD 215686 (422854080), V* IM Aur (440149808), V* FT UMa (448672304), V* HQ UMa (501747008), HD 96971 (575541080).

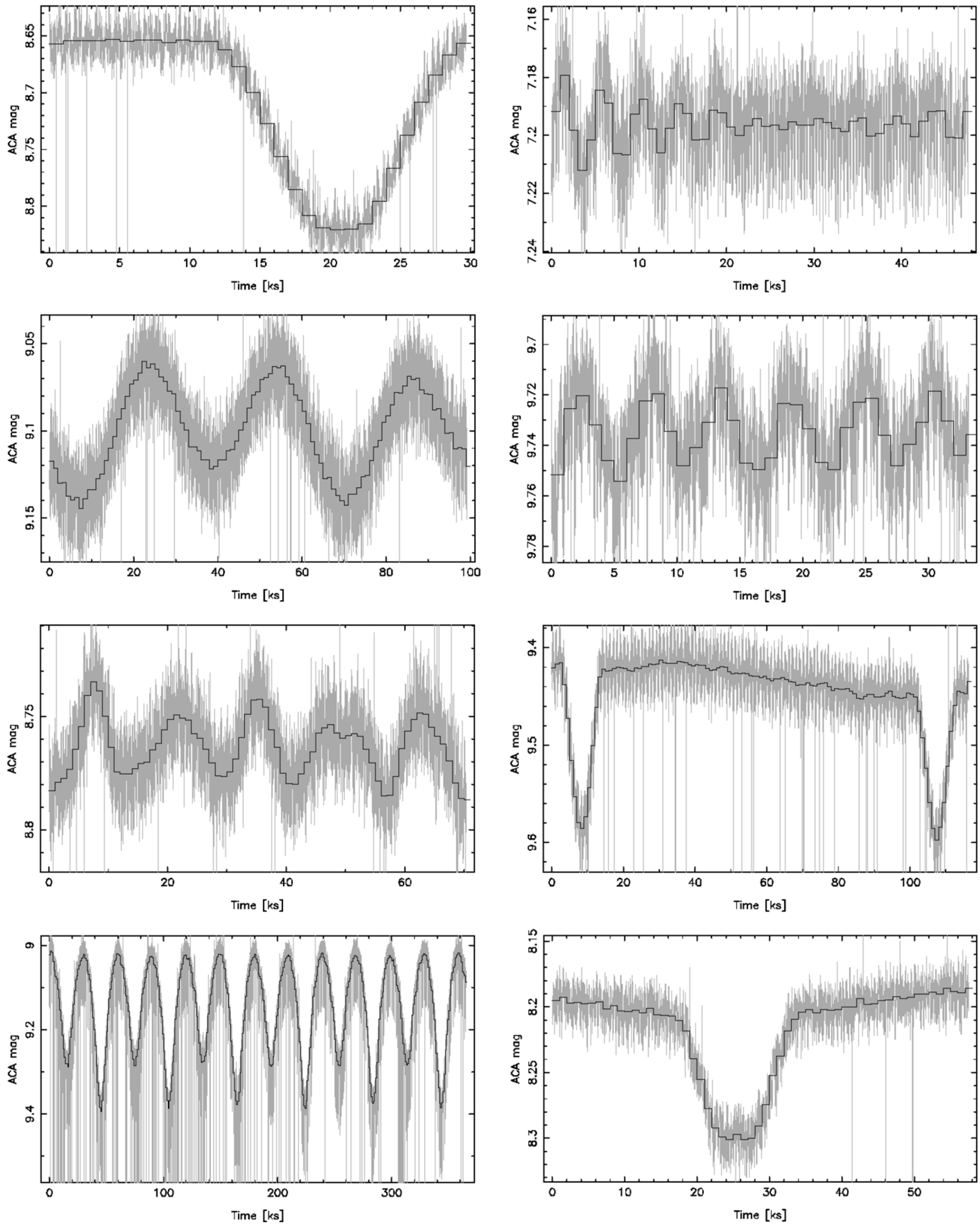


**Figure 10.** Examples of variable stars in the VGUIDE catalog. Observations are of varying lengths, as indicated on the *x*-axis. The gray lines represent the actual data at the instrument resolution. The black line represents a 1 ks binning of the data. From left to right, top to bottom: HD 180641 (AGASC_ID 62408720), HD 36843 (625745136), HD 15424 (692327352), HD 84943 (719066064), HD 98490 (722346384), V* VV Crt (797578040), SV* BV 616 (834145862), V* BQ Cap (834932760).

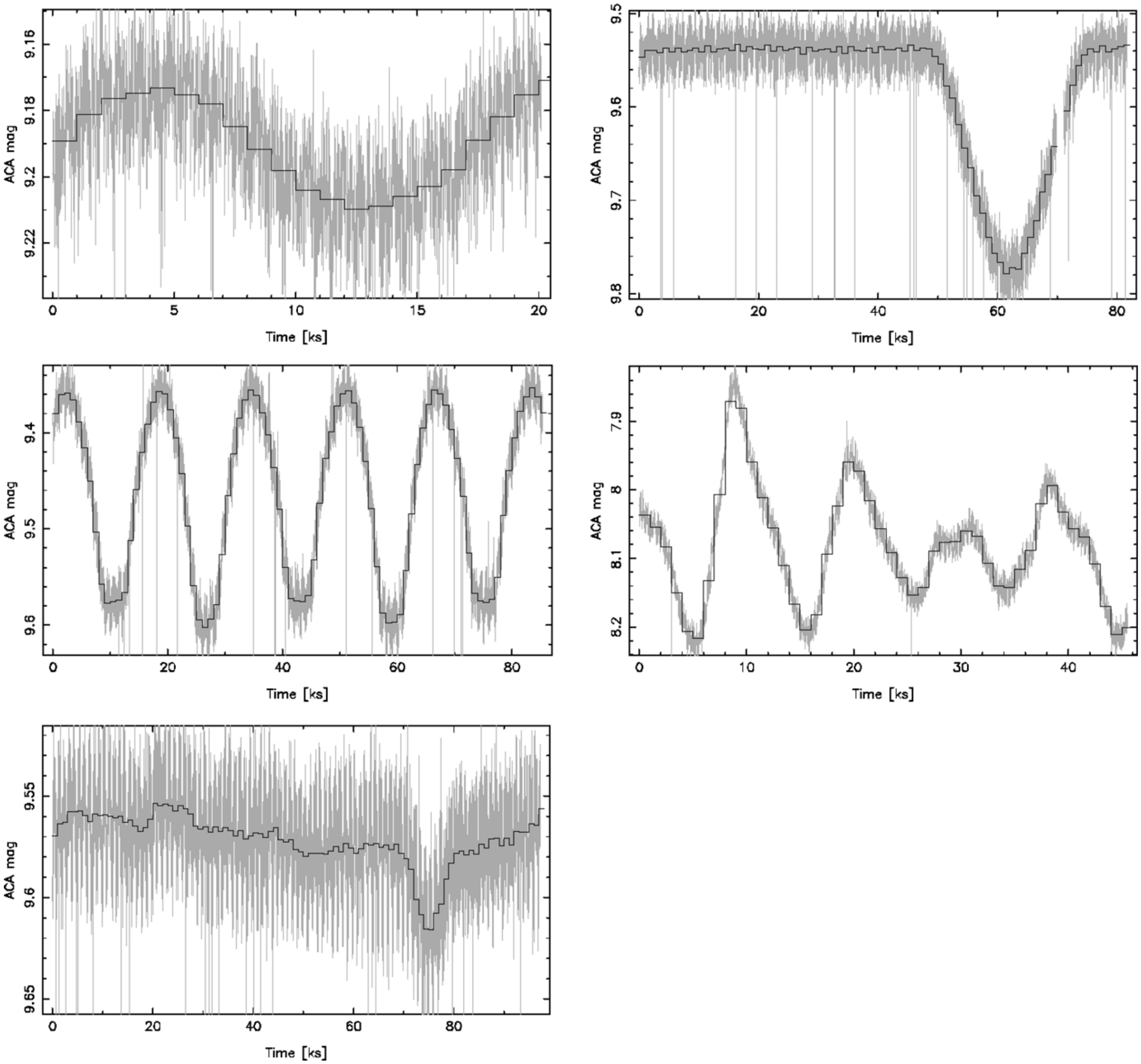


**Figure 11.** Examples of variable stars in the VGUIDE catalog. Observations are of varying lengths, as indicated on the *x*-axis. The gray lines represent the actual data at the instrument resolution. The black line represents a 1 ks binning of the data. From left to right, top to bottom: HD 164741 (AGASC_ID 897323144), HD 169623 (898777808), SV* BV 1004 (912136496), V* V703 Sco (967448688), HD 261171 (98316104).

DSCT or DSCTC was assigned. Sinusoidal light curves were generally designated `Indeterminate`. Many more stars may be pulsators than our categories indicate, and some of the pulsators may be rotating or spotted stars. We assigned the category `Indeterminate` if there were less than 3–4 complete pulsation cycles, if the light curve noise level was high, or if the light curve appeared to possibly be sinusoidal. It is probable that many of the stars we have categorized as `Indeterminate` will be reclassified as `Pulsators` when additional data are available.

Stars were assigned the category `Eclipsing Binary` even if only one full or a partial eclipse was seen. In particular, a flat-bottomed minimum was always interpreted as a signature of an eclipse. In addition, light curves with signature shapes of contact binaries (W UMa stars) were categorized as EW stars regardless of how many eclipses were seen.

We handled the B (both B and Be) stars differently than the other spectral types. There are several classes of variability for B stars: $\beta$ Cep (BCep), $\alpha^2$ Canum Venaticorum (AVC) magnetic rotators (generally A stars, but possibly B9), eruptive variables including $\gamma$ Cas, radial and non-radial pulsations, variations in Be star disk evolution (non-repeatable variation on timescales of weeks to months), and long period variable B stars (pulsating B stars with periods longer than a day). Differentiating between these types of variability, particularly with Be stars included in the group, requires more data than we have available in the VGUIDE. Therefore we assigned the majority of B stars that had not previously been identified as variable the category `Indeterminate`, including the Be stars.

The variable categories and classifications determined by us are limited to the *Chandra* guide star data set, and as mentioned previously, are very conservative. Additional photometry and

**Table 6**
Unusual and Interesting VGUIDE Stars

| AGASC No. | Star Name | Comment |
|---|---|---|
| 98316104 | HD 261171 | Eclipsing, exoplanet? |
| 260182304 | HD 103418 | Eclipsing |
| 309330608 | HD 281155 | EW |
| 322840728 | TYC 2463-1299-1 | Likely eclipsing |
| 420100064 | HD 213616 | Indeterminate |
| 448672304 | V* FT UMa | EW (we disagree with VSX classification) |
| 452329856 | BD+49 2042 | Possible exoplanet |
| 558900672 | HD 214007 | Eclipsing |
| 652608240 | HD 123981 | Indeterminate |
| 659822336 | HD 147026 | Indeterminate, eclipse or outburst |
| 722346384 | HD 98490 | DSCTC |
| 759957904 | HD 205065 | Indeterminate |
| 763502704 | HD 220687 | Rare eclipsing system with pulsating component |
| 896403224 | HD 160665 | Indeterminate, lots of data available |
| 934296912 | HD 66623 | Indeterminate |
| 966263464 | HD 154217 | Indeterminate |
| 966265784 | HD 154243 | Multiple modes, last reference from 1983 |
| 981468016 | HD 208213 | Indeterminate, lots of data |
| 1024208208 | CCDM J14371-4145AB | Indeterminate, possibly eclipsing |
| 1126968216 | HD 85938 | Indeterminate, possible rad zone contamination? |
| 1155010576 | CD-56 8417 | Eclipsing |
| 1248071160 | V* UV Oct | Known RR Lyr, beautiful curve |

period analysis will be needed to make more specific estimates. There are many opportunities for research projects using the *Chandra* VGUIDE data, including pulsational studies, contact binary analysis, and B star instabilities. Virtually all of the possible lines of investigation would need additional temporal data as well as spectroscopic studies. Many investigations would benefit from period-folding algorithms of all available *Chandra* data. To focus attention on specific research opportunities, we have collected stars in the VGUIDE catalog that would be appropriate for certain investigations, as well as objects with particularly intriguing features that are not easily understood. Table 5 lists the VGUIDE stars with at least 1000 ks of total exposure time. Table 6 is a collection of particularly unusual or interesting variable stars. Table 7 lists a few stars that could be candidates for shallow eclipsing binaries or exoplanets.

### 5.2. *Characteristics of VGUIDE*

In this section, we use the spectral classification of the stars to derive some statistics on various characteristics of the VGUIDE catalog. The source of the spectral types is SIMBAD. Approximately 5% of the accepted VGUIDE variable stars do not have a spectral class available in SIMBAD and have been omitted from our statistics. The spectral type distribution of all guide stars used in *Chandra* observations is shown in Figure 12. There are very few O or M stars among the guide stars. Representation increases from B through G spectral classes. The largest spectral group is K stars.

Figure 13 is a histogram of the number of accepted variable stars in VGUIDE according to spectral type. Note that the $y$-axis of Figure 12 has a log scale, while the $y$-axis of Figure 13 has a linear scale. Nevertheless, the distribution is very different from Figure 12, with the largest numbers of stars falling in the A and F spectral classifications, followed by B-type stars. Relatively few K stars are present. Tabulation of the number of variable stars detected in each spectral class, sorted by the type of variable, is shown in Table 8.

Figure 14 consists of several plots of the percentage of observed guide stars found to be variable as a function of spectral type. The plot on the left shows the percentage of all variable stars by spectral type. The fraction of previously unknown variables is overplotted for comparison. The large percentage of variable O stars is based on very few statistics. Only seven O stars are accepted variables in VGUIDE, with two being previously known variables. Eight percent of the B-type guide stars used by *Chandra* were identified as variable, although we include in this class the Be stars, which vary ubiquitously. While it is true that the B stars in this study are subject to small number statistics and the errors can be quite large, it is also true that any B star selected as a guide star will have a large negative $B-V$ and be significantly reddened. So this sample of B stars may be peculiar and may be associated with dust or shells. Of the A and F stars used as guide stars by *Chandra*, 2%–4% were found to

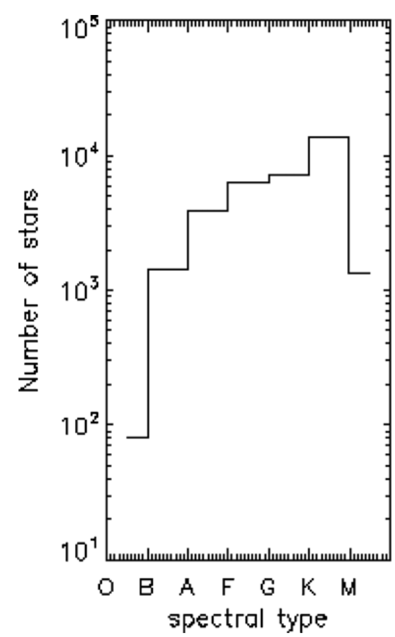


**Figure 12.** Histogram of spectral types of all observed guide stars with spectral type information in SIMBAD. The $y$-axis has been plotted as log values.

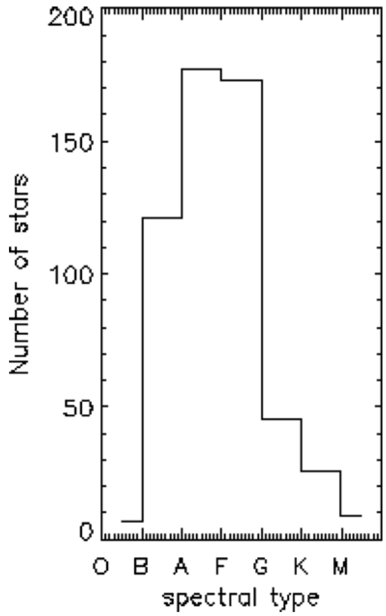


**Figure 13.** Histogram of spectral types of all guide stars found to be variable and having spectral classifications in SIMBAD.

be variable. Note that more than half of the A and F stars found to be variable were previously unidentified as variables. The second plot in Figure 14 shows the percent of identified variable stars that were classified in VGUIDE as pulsators. Between 40% and 50% of the A and F stars found to be variable have been classified as pulsators. The M star statistics in this plot are misleading because there are only nine M stars in VGUIDE, eight of which were previously identified as pulsators.

A histogram of the percentage of stars classified as eclipsing binaries by spectral type is shown in the third from the left plot in Figure 14. The histogram shows the percentage of eclipsing binaries is 20%–30% for all spectral types except O and M. For the eclipse to be seen in the light curve, the binary system must be in a very narrow range of inclination, or be a very close binary system.

The far right plot in Figure 14 shows the percentage of identified variable stars that were classified by us as `Indeterminate`. We tended to classify most B and Be stars as `Indeterminate`. The cycles tend to be long for these stars and in general we have data for only a partial cycle. In addition, we tended to classify A and F stars as `Indeterminate` for the lowest amplitude variations and for apparent pulsators with less than three cycles in the light curve.

A color–magnitude diagram of the guide stars is shown in Figure 15. The diagram has been restricted to show only those stars with parallax values available from *Hipparcos* (about 30% of the guide stars). Absolute magnitude was calculated from parallax and apparent magnitude from *Hipparcos*. The $B-V$ values are from the AGASC catalog. No reddening correction has been applied. Black dots are *Chandra* guide stars that do not show any variability. Red diamonds are *Chandra* guide stars

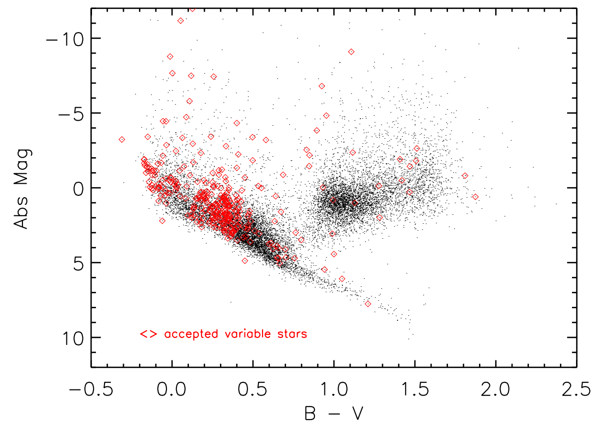


**Figure 15.** Color vs. absolute mag diagram for stars with parallax measurements. Stars in the AGASC catalog are indicated with a black dot and all stars identified as VGUIDE variables are indicated with a red diamond. Note that no extinction correction has been applied.

**Table 7**
Possible Shallow Eclipsing Binary or Exoplanet Detections Among VGUIDE Stars

| AGASC No. | Star Name | Comment |
|---|---|---|
| 452855440 | BD+48 2009 | 0.01 mag single dip; G8III |
| 98316104 | HD 261171 | 97 ks; 0.03 mag; one dip F2V |
| 21118440 | HD 50725 | 10 ks; 0.03 mag single dip; A3 |
| 378279000 | HD 26395 | Eclipse; 7 ks wide 0.05 mag deep; F4V |
| 649856976 | BD-00 2666 | 77 ks; one 0.02 mag dip; scan noisy |
| 114037536 | HD 102809 | 10 ks; dip 0.03 mag |
| 283124448 | HD 194888 | 10 ks; 0.04 mag dip |
| 452329856 | BD+49 2042 | 10 ks; 0.02 mag dip; K2 |
| 261112008 | HD 109306 | 10 ks; 0.02 mag dip; F3V |

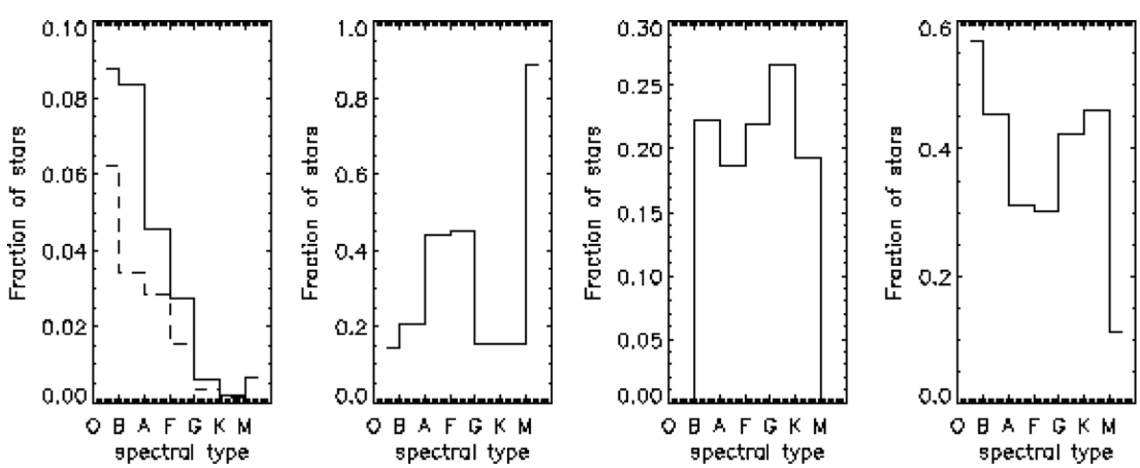


**Figure 14.** Left: fraction of total guide stars observed that were found to be variable vs. spectral class. The dotted line represents the fraction of previously unknown variable stars that were found vs. spectral class. Middle left: fraction of variable guide stars classified as pulsators vs. spectral class. Middle right: fraction of variable guide stars found to be eclipsing binaries vs. spectral class. Right: fraction of variable guide stars classified as Indeterminate vs. spectral class.

**Table 8**
Distribution of VGUIDE Variables with Spectral Type

| Spec Type | No. of Stars | No. of Variables | No. of Previously Unknown Variables | No. of Pulsators | No. of Eclipsing Binaries | No. of Indeterminate |
|---|---|---|---|---|---|---|
| O | 80 | 7 | 5 | 1 | 0 | 4 |
| B | 1444 | 121 | 49 | 25 | 27 | 55 |
| A | 3881 | 177 | 111 | 78 | 33 | 55 |
| F | 6360 | 173 | 98 | 78 | 38 | 52 |
| G | 7257 | 45 | 24 | 7 | 12 | 19 |
| K | 13616 | 26 | 16 | 4 | 5 | 12 |
| M | 1332 | 9 | 1 | 8 | 0 | 1 |

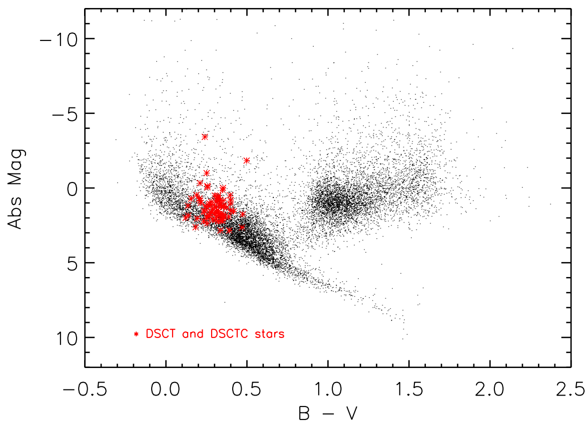


**Figure 16.** Color vs. absolute mag diagram for DSCT and DSCTC stars with parallax measurements. Stars in the AGASC catalog are indicated with a black dot and all stars identified in VGUIDE as DSCT or DSCTC variables are indicated with a red diamond. Note that no extinction correction has been applied.

that do show variability and appear in the VGUIDE catalog. The main sequence and red giant branch are readily seen. There is a strong clustering of VGUIDE variable stars at about absolute magnitude of +2 and $B - V$ of 0.02. These are the $\delta$ Sct stars as classified previously as well as in this paper (Figure 16). The tight concentration of the $\delta$ Sct indicates that our classification methods are reasonably accurate.

Detection of exoplanets may be possible with the data in VGUIDE. Exoplanets are expected to produce a flux drop of less than a few percent in the parent star. The flux drop is dependent on the size of both the parent star and the planet. Our ability to detect 0.02–0.04 mag changes in the VGUIDE light curves of 7.0–10.0 mag stars implies that a search for evidence of exoplanets in the VGUIDE catalog may be fruitful, although it is difficult with the VGUIDE data to differentiate between shallow-eclipsing stellar systems and exoplanets. Table 7 is a list of VGUIDE stars that might show evidence of shallow-eclipsing or exoplanet transits, but there are many more possible exoplanet light curves in VGUIDE.

## 6. CONCLUSIONS

The *Chandra* VGUIDE Catalog was created by a method of detecting variable stars using routinely available, non-proprietary data products from a space mission. We have collected information on all guide stars that appeared variable by examination of their light curves for approximately 9 years of the *Chandra* mission. VGUIDE contains 827 definite and possible variable stars to an amplitude limit of 0.02–0.03 mag identified by visual inspection of the *Chandra* guide star light curves. At least 319 of these stars are newly identified variable stars. For each previously unknown variable star, we assigned a variable category and classification using the definitions of GCSV. These classifications are based only on the light curves available from the VGUIDE catalog and may be revised in the future when more data are available or with further analysis. As expected, A and F stars tend to have single and multiple-mode pulsations.

There are several advantages to searching for variable stars with space mission optical pointing control cameras. The observations are made above the atmosphere, eliminating the problems of seeing, scintillation, and absorption characteristics in Earth's atmosphere. The instrumentation is simple and extremely stable photometrically, as the health and safety of the entire space mission depends on the pointing control. The positions are precisely known. Depending on the orbit of the satellite, guide star light curves can be several days long. Such long continuous light curves are not available from the ground. For the *Chandra* mission in particular, the CCD exposure time of 1.7 s allows excellent temporal coverage. We anticipate that a few other space missions will have guide star light curves of sufficient quality and length to allow similar discoveries to those discussed here. We find VGUIDE is most sensitive to short period (∼hr) variability detection.

We have not done period searches or any type of automated variability detection procedures on the data in the catalog. Certainly there are sufficient data for many stars to derive epochs and periods, or identify pulsation modes, which are often multiple. In addition, complementary observations from the ground can provide sufficient information for detailed analysis of many objects.

The VGUIDE Catalog is available on the Web with a user interface that allows sorting of the stars on various characteristics and light curves for each star with mouse hovering. The star detail page for each star has all of the light curves available for download. We are identifying more variable guide stars as the *Chandra* mission continues. In general, 1–2 new variable stars are identified each week from the guide star data of new *Chandra* observations. In addition, there is a significant number of variable guide stars now identified from the first few months of the mission. Cone searches by position and other sorting capabilities are planned in the near future. New releases of the VGUIDE catalog will include these stars and will be announced in the *Chandra* Bulletin and via the *Chandra* Web site and the AAVSO Web site.

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*Facilities:* CXO

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