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STATISTICAL PROPERTIES OF GALACTIC δ SCUTI STARS: REVISITED

S.-W. Chang[1], P. Protopapas[2,3], D.-W. Kim[1,2,4], and Y.-I. Byun[1]
[1] Department of Astronomy, Yonsei University, Seoul 120-749, Korea; seowony@galaxy.yonsei.ac.kr, kim@mpia-hd.mpg.de
[2] Harvard Smithsonian Center for Astrophysics, Cambridge, MA 02138, USA
[3] Institute for Applied Computational Science, School of Engineering and Applied Sciences, Harvard University, Cambridge, MA 02138, USA
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ABSTRACT

We present statistical characteristics of 1578 δ Scuti stars including nearby field stars and cluster member stars within the Milky Way. We obtained 46% of these stars (718 stars) from work by Rodríguez and collected the remaining 54% of stars (860 stars) from other literature. We updated the entries with the latest information of sky coordinates, color, rotational velocity, spectral type, period, amplitude, and binarity. The majority of our sample is well characterized in terms of typical period range (0.02–0.25 days), pulsation amplitudes ($<$0.5 mag), and spectral types (A–F type). Given this list of δ Scuti stars, we examined relations between their physical properties (i.e., periods, amplitudes, spectral types, and rotational velocities) for field stars and cluster members, and confirmed that the correlations of properties are not significantly different from those reported in Rodríguez's work. All the δ Scuti stars are cross-matched with several X-ray and UV catalogs, resulting in 27 X-ray and 41 UV-only counterparts. These counterparts are interesting targets for further study because of their uniqueness in showing δ Scuti-type variability and X-ray/UV emission at the same time. The compiled catalog can be accessed through the Web interface http://stardb.yonsei.ac.kr/DeltaScuti.

Key words: catalogs – stars: variables: delta Scuti – ultraviolet: stars – X-rays: stars

Online-only material: machine-readable and VO tables

1. INTRODUCTION

Observation of pulsating variable stars is a unique approach to studying internal stellar structures and evolutionary status across a broad range of stellar types (Gautschy & Saio 1996). Typical examples of pulsating variables are hydrogen-rich DA white dwarfs, Cepheids, RR Lyraes, δ Scutis, and γ Doradus stars. In particular, δ Scuti stars (hereinafter δ Sct stars) have attracted much attention in recent years because of their great number of radial and non-radial pulsation modes driven by the κ mechanism that mostly works in the He II ionization zone (e.g., Gautschy & Saio 1995; Breger et al. 1998, 2002, 2005; Rodríguez & Breger 2001). They are located at the lower part of the instability strip occupied by main sequence (MS), pre-main-sequence (PMS), and more evolved stars, and are characterized by relatively short-period and low-amplitude variability. It is well known that periods of classical δ Sct stars are in the range of 0.02–0.25 days, with amplitudes between 0.003 and 0.9 mag in the V band.[5] Note that the lower end of these amplitude values is just an observational limit of the ground-based surveys. *Kepler* has detected a large number of δ Sct stars whose amplitudes are lower than 0.003 mag (e.g., Uytterhoeven et al. 2011; Balona & Dziembowski 2011b). Also classical δ Sct stars have masses between 1.6 and 2.4 $M_\odot$ for near solar-metallicity stars, and between 1.0 and 1.3 $M_\odot$ for metal-poor ($-1.5 <$ [Fe/H] $<$ -1.0) stars (McNamara 2011). A number of detailed reviews describe δ Sct stars and associated issues (e.g., see Breger 2000; Rodríguez & Breger 2001; Lampens & Boffin 2000, and references therein).

In order to update the statistical view of pulsational and physical characteristics of Galactic δ Sct stars, we collected a large sample of δ Sct stars from (1) the catalog of δ Sct-type variables (Rodríguez et al. 2000, hereinafter R2000), (2) the catalog of SX-Phe-type variables in globular clusters (GCs; Rodríguez & López-González 2000), and (3) other individual findings after R2000 (e.g., Henry et al. 2001; Dallaporta et al. 2002; Sokoloski et al. 2002; Rodríguez et al. 2003; Bernhard et al. 2004; Chapellier et al. 2004; Henry & Fekel 2002; Escolà-Sirisi et al. 2005; Martín-Ruiz et al. 2005; Zhang et al. 2006; Christiansen et al. 2007; Jeon et al. 2007; Peña et al. 2007; Hartman et al. 2008; Pigulski et al. 2009; Sokolovsky 2009; Soydugan et al. 2009). Note that we compiled δ Sct stars that appeared in the literature published before 2011.

Not surprisingly, the quantitative increase of δ Sct stars is due to an increasing number of long-term variability observations that surveyed a large fraction of the sky. MACHO (Alcock et al. 2000) and OGLE (Udalski et al. 1997) monitored the Galactic bulge for several years, and discovered a number of pulsating variables including δ Sct-type variables. Other wide-field all-sky surveys also detected more than 500 δ Sct stars (ROTSE: Blake et al. 2003; Jin et al. 2003; ASAS: Pojmanski et al. 2006; TAOS: Kim et al. 2010). In order to study the low-amplitude oscillations of the pulsators in the cluster, several individual observations monitored nearby open clusters (OCs) with an age range from 0.012 to 2.8 Gyr (e.g., Freyhammer et al. 2001; Arentoft et al. 2005; Martín-Ruiz et al. 2005; Kang et al. 2007; Anderson et al. 2009; Jeon 2008, 2009a, 2009b) and found nearly 100 δ Sct stars. In addition, a large number of metal-poor δ Sct stars (SX Phe stars) have been discovered even in the central regions of GCs (Pych et al. 2001; Bruntt et al. 2001; Jeon et al. 2001, 2003; Mazur et al. 2003; Jeon et al. 2004; Kopacki 2005; Olech et al. 2005; Kopacki 2007; Arellano Ferro et al. 2008, 2010) using improved photometry techniques (e.g., difference image analysis). The GCVS (Samus et al. 2009) also provides another ∼400 pulsating stars designated as DSCT or

[4] Current address: Max Planck Institute for Astronomy, Königstuhl 17, D-69117 Heidelberg, Germany.
[5] The pulsation amplitude has an intrinsic dispersion caused by the range of periods and amplitudes, and so we adopt the amplitude range that is defined in the GCVS variability classification scheme (see http://www.sai.msu.su/gcvs/gcvs/iii/vartype.txt).

DSCTC. DSCTs are variables of the δ Sct-type that are close to the SX Phe-types, while DSCTCs are a low-amplitude group of δ Sct variables ($\Delta V < 0.1$ mag). From the above literature, we include all pulsating stars mentioned as δ Sct stars for this work.

In Section 2, we describe procedures for selecting typical δ Sct stars and brief information of the catalog format. In Section 3, we present statistical distributions of physical properties and their relationships. In Section 4, we present lists of X-ray/UV counterparts and their characteristics. A concluding summary is presented in the last section.

2. CATALOG COMPILATION

We first collected the largest possible samples of field and cluster δ Sct stars that were identified by previous studies as typical δ Sct-type stars. The catalog contains subclasses of δ Sct stars showing clear differences in metal abundances due to diffusion and other processes (Rodríguez & Breger 2001) and are thus representative of chemically peculiar δ Sct stars' diversity such as:

1. The group of λ Bootis-(λ Boo-) type stars that are defined as metal-poor (except C, N, O, and S elements which have a solar abundance) Population I objects (Paunzen et al. 1997).
2. The classical and evolved (ρ Pup and δ Del) metallic-line stars (Am stars), which are characterized by an underabundance of C, N, O, Ca, and Sc, as well as by an overabundance of the Fe group and heavier elements (Hareter et al. 2011).
3. Metal-poor SX Phe stars of Population II and the old disk population.

We also include the coolest subgroup of Ap stars known as the rapidly oscillating Ap (roAp) stars. Among them, δ Sct- or γ Dor-type pulsations are clearly present (Balona et al. 2011a). The final group is a small number of pulsating PMS stars. PMS pulsators with masses between 1.5 and 4 $M_\odot$ are known to have consistent spectral types, luminosities, and pulsation modes with classical δ Sct stars (Zwintz 2008).

We removed all stars that turned out not to be δ Sct stars by later studies. These stars are either W UMa and RR Lyrae stars, or stars showing no evidence of periodicity in their light curves (e.g., V1241 Tau: Arentoft et al. 2004). Finally, our catalog contains 1578 δ Sct stars within our Galaxy, which provides relatively more complete and up-to-date entries than previous works of a similar nature (R2000; Rodríguez & López-González 2000). The number of pre-existing and newly listed δ Sct stars is summarized in Table 1. The total number of δ Sct stars, including 1282 field stars and 296 cluster member stars, is increased by a factor of two in comparison with the existing catalogs.

In order to eliminate duplicated entries and to extract their additional physical parameters, all δ Sct stars in the catalog were cross-matched with the VizieR CDS database (Genova et al. 2000) either by their designations (i.e., HD, HIP, or GCVS designation) or by a radial search. Table 2 shows the catalogs cross-matched with the δ Sct stars.

2.1. Catalog Description

Table 3 presents our catalog of δ Sct stars which lists the IDs, coordinates (J2000.0), mean magnitudes, periods, amplitudes, rotational velocities, binarities, and spectral types with comments. In addition, we specified the membership for each δ Sct star by three groups: Milky Way field stars (MWF), GC member stars, and OC member stars, respectively.

Table 1
Number of δ Sct Stars

Sources	Existing Catalogs[a]	This Work[b]	References
Hippacros	78	78	Perryman et al. (1997)
OGLE[c]	52	52	Udalski et al. (1997)
MACHO[d]	81	81	Alcock et al. (2000)
ROTSE[e]	...	4	Jin et al. (2003)
ASAS[f]	...	525	Pojmanski et al. (2006)
TAOS[g]	...	41	Kim et al. (2010)
GCVS[h]	294	419	Samus et al. (2009)
Open clusters	64	92	List A[i]
Globular clusters	123	204	List B[j]
Miscellaneous	26	82	Individual papers
Total	718	1578	

Notes.
[a] The catalogs compiled by R2000 and Rodríguez & López-González (2000).
[b] This number (Column 3) is inclusive of both pre-existing (Column 2) and newly listed δ Sct stars.
[c] Optical Gravitational Lensing Experiment.
[d] MAssive Compact Halo Object.
[e] Robotic Optical Transient Search Experiment.
[f] All-Sky Automated Survey.
[g] Taiwan-American Occultation Survey.
[h] General Catalog of Variable Stars.
[i] List A: α Persei, Pleiades, Hyades, Praesepe, Melott 71, NGC 2682, NGC 3496, NGC 5999, NGC 6134, NGC 6882, NGC 7062, NGC 7245, NGC 7654, IC 4756.
[j] List B: ω Cen, 47 Tuc, IC4499, M3, M4, M5, M13, M15, M53, M55, M56, M68, M71, M92, NGC 288, NGC 3201, NGC 4372, NGC 5053, NGC 5466, NGC 5897, NGC 6362, NGC 6366, NGC 6397, NGC 6752, Ru 106.

ID. The numbering of stars in the catalog is in order of increasing right ascension, labeled as DS1–DS1578. We retain the previous numbering system from R2000 and Rodríguez & López-González (2000) which is available in the online version of the journal.

Magnitudes. Our catalog lists the apparent magnitude m_V (or m_B) which is denoted by V (or B) for all objects, and includes at least V magnitude, if available, from one of the catalogs listed in Table 2. In the OGLE and ASAS surveys, V magnitude is calculated as $V = \min(V)$ (minimum magnitude) + $\Delta V/2$ (half-amplitude of variability). Except for 17 stars, all δ Sct stars in the catalog have V magnitude.

Period and amplitude. Many light curves of δ Sct stars show signs of multiperiodicity due to the simultaneously excited radial and/or non-radial modes (e.g., Kiss et al. 2002). However, we list only the periods and amplitudes that correspond to the dominant primary periodicity in the period search. Similar to the previous definition in R2000, amplitudes correspond to the full amplitudes (ΔV) of periodic variations in the V band. If reliable amplitude estimation is not available, we defined the amplitude as the difference between the maximum and minimum V magnitude.

Rotational velocity. We used three dedicated catalogs (Glebocki & Stawikowski 2000; Royer et al. 2007; Bush & Hintz 2008) to extract the projected rotational velocities ($v \sin i$) and found $v \sin i$ for about 10% of the stars. Due to the differences between the methods for measuring stellar rotation, these catalogs often present slightly different values for $v \sin i$. Royer et al. (2007) noticed that there is a systematic deviation of each method and used their Fourier transform scale of $v \sin i$. On the other hand, Bush & Hintz (2008) examined the relation between their measured $v \sin i$ values and the average $v \sin i$ values from

Table 2
Catalogs Used to Extract Additional Parameters

Catalog Name	References
Henry Draper Catalog and Extension	Cannon & Pickering (1993)
HDE Charts: Position, Proper Motions	Nesterov et al. (1995)
The Hipparcos and Tycho Catalogs	Perryman et al. (1997)
Catalog of Projected Rotational Velocities	Glebocki & Stawikowski (2000)
The Catalog of Components of Doubles and Multiples	Dommanget & Nys (2002)
NOMAD Catalog	Zacharias et al. (2005)
The Guide Star Catalog, Version 2.3.2	Lasker et al. (2006)
Rotational Velocities of A-type Stars. III. Velocity Dispersions	Royer et al. (2007)
Rotational Velocity Determinations for 118 δ Sct Variables	Bush & Hintz (2008)
General Catalog of Variable Stars	Samus et al. (2009)
All-Sky Compiled Catalog of 2.5 Million Stars	Kharchenko & Roeser (2009)
AAVSO International Variable Star Index VSX	Watson et al. (2009a)
The Washington Visual Double Star Catalog	Mason et al. (2009)
Catalog of Stellar Spectral Classifications	Skiff (2009)

Table 3
New Catalog of δ Sct Stars

ID	R.A. (h:m:s)	Decl. (d:m:s)	V (mag)	B (mag)	Period[a] (days)	ΔV[b] (mag)	$v \sin i$ (km s^{-1})	SpType	S/P[c]	B/M[d]	Type[e]	GCVS (name)
1	00 00 53	+62 25 15	15.80			0.40				0	MWF	V0878 Cas
2	00 01 16	−60 37 00	9.93	10.33	0.1221	0.35		A8V	S	0	MWF	
3	00 01 16	+06 47 29	7.23	7.62	0.1652	0.04	135	F0	P	0	MWF	DR Psc
4	00 04 00	+12 08 45	7.26	7.62	0.1701	0.06	74	F0III	S	1	MWF	NN Peg
5	00 04 12	−20 55 06	11.66		0.1790	0.17				0	MWF	
6	00 05 54	+11 28 18	13.59		0.1588	0.52				0	MWF	

Notes.
[a] Period corresponds to the dominant pulsation mode.
[b] Peak-to-peak magnitude.
[c] Spectroscopic spectral type: S; photometric spectral type: P.
[d] Single stars: 0; binary or multiple stars: 1.
[e] Milky Way field stars: MWF; open cluster member stars: OC; globular cluster member stars: GC.

(This table is available in its entirety in machine-readable and Virtual Observatory (VO) forms in the online journal. A portion is shown here for guidance regarding its form and content.)

the published literature, and concluded that there is no systematic offset within the error of each measurement. Here we simply selected $v \sin i$ values from the most recently published data, regardless of measuring methods.

Spectral type. We compiled the spectral-type information primarily based on the catalog by Skiff (2009), which includes only spectral types determined from spectra (i.e., line and band strengths or ratios). The spectral types are expressed in the MK notation only for δ Sct stars. We do not list the individual spectral types of binary companions. When the spectroscopic spectral types are not available, we took the spectral types determined from photometry or inferred from broadband colors. In our catalog, we found spectroscopic spectral types (denoted as "S" in the catalog) for 15% of the stars and photometric estimates (P) for 9% of the stars, respectively.

Binarity. It is known that many δ Sct stars are components of binary or multiple star systems (see Figure 2 of Zhou 2010), and that their pulsation properties may be modified by binarity (Lampens & Boffin 2000). We searched the double star catalogs (Nesterov et al. 1995; Dommanget & Nys 2002; Mason et al. 2009) and found information on binarity for 141 stars, which are indicated by flag "1."

3. STATISTICAL PROPERTIES OF δ Sct STARS

3.1. Histograms of the Pulsational Properties and the Physical Properties

In this section, we present histograms that describe the distribution of each parameter (magnitude, period, amplitude, $v \sin i$, and spectral type) for all δ Sct stars according to their membership groups (i.e., MWF, GC, or OC) defined in the previous section. The members of binary or multiple star systems are excluded from the histograms to reduce potential contamination of the parameters.

Figure 1 shows the histogram of the V magnitudes for 1417 δ Sct stars. In the magnitude distribution of field δ Sct stars, two separated peaks appear as a signature of the observational selection effect caused by the different V magnitude range of different variability surveys. For example, the δ Sct stars between 16 and 20 mag were detected by the MACHO and OGLE surveys, while many bright stars ($6 < V < 10$) were observed by the *Hipparcos* survey. Because the absolute V magnitude of classical δ Sct stars is relatively faint ($M_V \sim$ 1–2.5), our samples of Galactic δ Sct stars generally have apparent magnitudes brighter than $V = 20$ (Alcock et al.

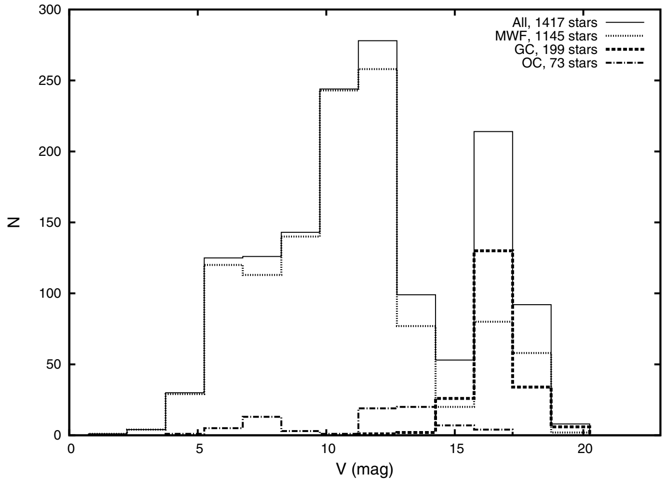

Figure 1. Magnitude histogram of the δ Sct stars. Each histogram represents the number of stars from the field regions (dotted line), the globular clusters (dashed line), the open clusters (dot-dashed line), and the combined entries (solid line).

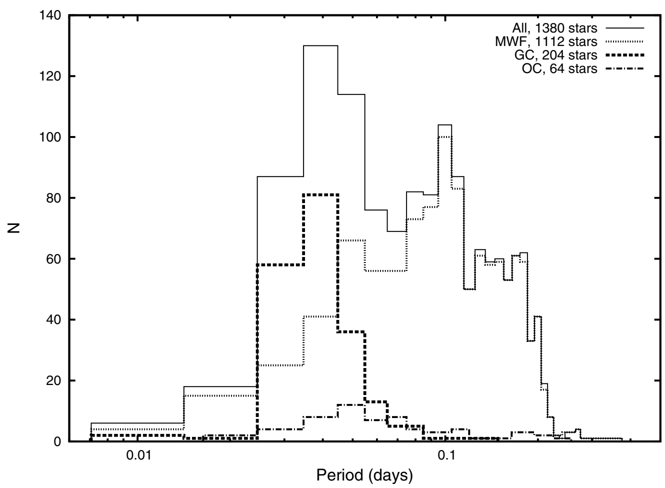

Figure 2. Period histogram of the δ Sct stars. The representation of the lines is the same as in Figure 1, but the x-axis is in logarithmic scale. The dominant periods are relatively short and range from 0.02 to 0.25 days, which is a typical characteristic of δ Sct stars.

2000). Thus, detection of distant δ Sct stars at the faint end of the histogram requires time-consuming observations where detection efficiency decreases.

Figure 2 shows that δ Sct stars are indeed short-period variables, with individual periods in the range from 0.02 to 0.3 days. In general, the period range of δ Sct stars is physically restricted between 0.02 and 0.25 days (Breger 2000). Our catalog includes the δ Sct stars with the shortest periods reported to date. There are two field stars (~0.018 days) from the TAOS two-year data (Kim et al. 2010) and two SX Phe stars (~0.017 days) in the GC ω Centauri (Olech et al. 2005). As mentioned by Rodríguez & Breger (2001), pulsating variables with periods between 0.25 and 0.3 days may need to be classified as evolved Population I δ Sct or Population II RRc (or γ Dor). Except for the binaries and multiple systems, nine stars belong to this period range. One interesting object among them is UY Cam which was originally regarded as RR-Lyrae-type. Because of its long period (0.267 days), low metallicity ($Z = 0.0037$), high luminosity ($M_V = -0.2$ mag), and low gravity ($\log g = 3.46$), this high-amplitude δ Sct star (HADS) has shared physical characteristics with not only the SX Phe stars but also the RR

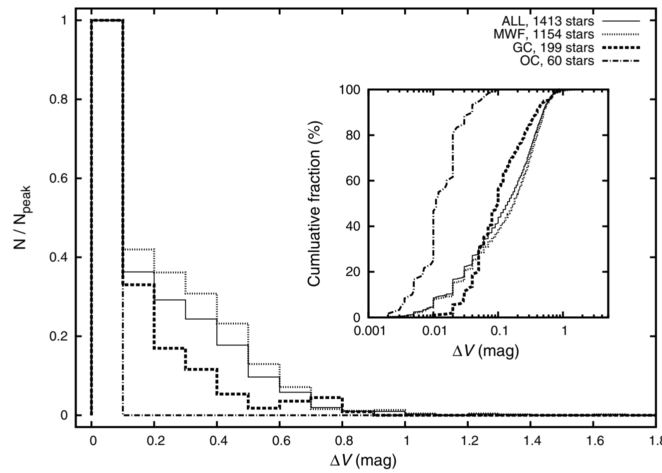

Figure 3. Normalized amplitude histogram of the δ Sct stars. All the histograms are normalized to their peaks. The representation of the lines is same as in Figure 1, but the histogram bin size is $0\overset{\mathrm{m}}{.}1$. The small inserted plot shows the cumulative distribution of the amplitudes. About 40% of the δ Sct stars have pulsation amplitudes smaller than $0\overset{\mathrm{m}}{.}1$.

Lyrae stars (see Zhou & Liu 2003, and references therein). Our catalog also includes two stars with periods longer than 0.3 days. V4063 Sgr (=HD 185969) with a period of 0.361 days has the longest period among any known δ Sct stars (McInally & Austin 1978), and BZ Boo (=HD 118743) has a period of 8–10 hr (Jackisch 1972). Further observations of these two stars are required to verify these periods and to confirm if they are δ Sct-type pulsators.

In contrast to the MWF, most SX Phe stars in GCs are short-period pulsators with periods less than 0.1 days. Recent observations show that the low metal abundance seems to lead to a shorter pulsation period (see Figure 7 of Rodríguez & López-González 2000; Figure 1 of McNamara 1997). According to theoretical models for the evolution of stars with low metal abundance, both fundamental (Π_0) and first-overtone (Π_1) modes are pulsationally unstable around $\log \Pi_0 = -1.0$ (Templeton et al. 2002). This shows that metal-poor stars enter pulsationally unstable states mostly at periods shorter than 0.1 days. On the other hand, some SX Phe stars with longer periods ($P > 0.1$ days) can be explained by post-main-sequence evolution (e.g., Bruntt et al. 2001).

Figure 3 shows both histograms and cumulative distributions of the amplitude of δ Sct stars. For comparison, the histograms are normalized to have a maximum value of unity. The amplitudes are in the range from 0.002 and 1.69 mag in the V band.[6] Historically, on the basis of their pulsation amplitudes, the δ Sct stars are divided into low-amplitude δ Sct stars (LADS) and HADS. Solano & Fernley (1997) adopted a value of $\Delta V = 0\overset{\mathrm{m}}{.}1$ as a criterion to distinguish LADS from HADS ($\Delta V \geqslant 0\overset{\mathrm{m}}{.}3$). This amplitude difference is substantially related to their pulsation modes and evolutionary states. Most of the LADS are on or close to the MS, and pulsate in non-radial p-modes, whereas HADS tend to be more evolved than LADS, and typically pulsate in low-order radial p-modes (Breger 2000; Alcock et al. 2000). Other researchers have suggested that the separation in amplitude is due to a difference in rotational velocities between the two groups (see Section 3.2 for details). In both young and intermediate age (0.012–2.8 Gyr) OCs, δ Sct stars tend to show only very low amplitudes (0.002–0.1 mags), while those in field stars

[6] Amplitudes in the B band are relatively lower than those in the V band.

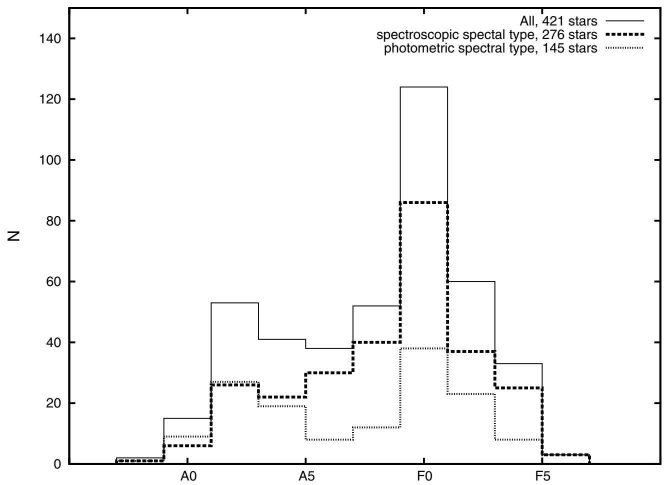

Figure 4. Spectral type histogram of the δ Sct stars. Generally there is good agreement between the overall distribution of the spectral types obtained from spectroscopic methods (dashed line) and photometric methods (dotted line).

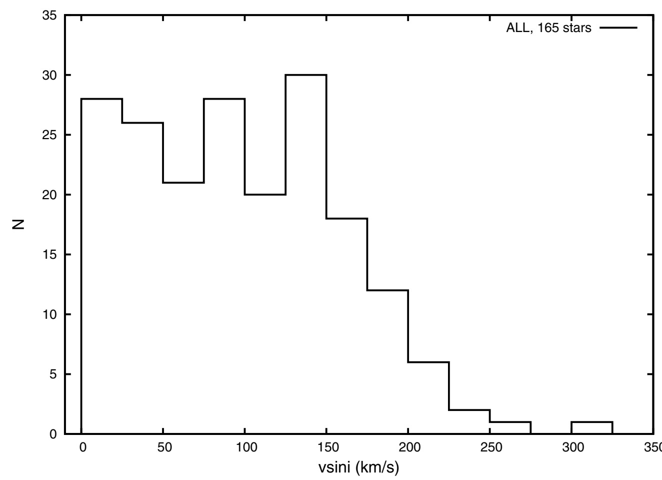

Figure 5. Projected rotational velocity ($v \sin i$) distribution of the δ Sct stars. The number of stars rapidly decreases above the rotational velocity of 150 km s^{-1} as shown in the histogram.

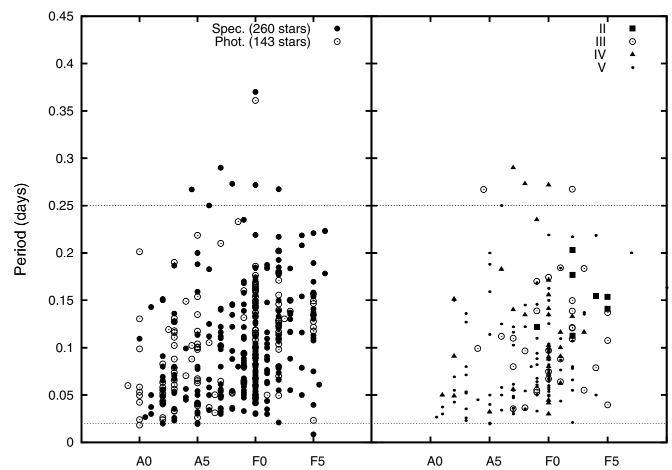

Figure 6. Relation between spectral type and period for the δ Sct stars. In the left panel, the distribution between the two parameters is shown for two groups of δ Sct stars with either spectroscopic (dots) or photometric (open circles) spectral types. In both cases, the early-type stars tend to have shorter periods than the late types. In the right panel, we indicate the same distribution with luminosity classes II–V by different symbols.

and GCs tend to have a large range of amplitudes through the two amplitude groups. The cumulative distributions represent that low-, medium-, and high-amplitude δ Sct stars discovered in GCs are in the ratio of 3:1:1, and those in field stars are in the ratio of 1.3:1:1.

Spectral types of δ Sct stars are given in Figure 4. Only 421 stars have either spectroscopic and/or photometric spectral types and their spectral types are between early-A and late-F type. Although δ Sct stars generally have spectral types ranging from about A2 to F2 (Breger 2000), our catalog includes some stars that lie outside the empirical instability strip. Many studies have tried to obtain more accurate constraints of the δ Sct instability strip close to the observed location and shape. The blue edge of the δ Sct instability strip is theoretically well constrained (see Pamyatnykh 2000), whereas the red edge is rather complicated and has a large range of possibilities for the slope and shape. Interestingly our sample includes a few blue outliers that span a range of spectral types from A0–A2. As suggested by Schutt (1993), the blue edge of the instability strip may need to be extended to include the early-A type stars. On the other hand, for the low-temperature stars close to the red edge, we have to consider the coupling effect between convection and oscillation together with the turbulent viscosity. Xiong & Deng (2001) calculated non-adiabatic oscillations for stars in the mass range 1.4–3.0 $M_{\odot}$ and matched the empirical red edge very well. According to Schmidt-Kaler (1982), this mass range is consistent with the spectral type of δ Sct stars between A0V and F5V. But despite a δ Sct-like pulsation nature, about 18 red outliers actually have spectroscopic/photometric spectral types later than F5, and thus relatively cool temperatures (e.g., VX Hya (F6) and DE Lac (kF3hF7)[7]). Further spectroscopic investigations are needed in order to remove non-δ-Sct stars around the blue and red edge of the instability strip.

Figure 5 shows the distribution of projected rotational velocities. The distribution of rotational velocity is almost uniform for velocities smaller than 150 km s^{-1}, and extends to 300 km s^{-1} which is 70% of break-up velocity for normal A type stars (Abt & Morrell 1995). Therefore, the break-up velocity is not a limiting factor for the rotational velocities of our samples. The broad range of rotation rates seen in δ Sct stars are in marked contrast to those of RR Lyrae stars, which have an upper limit for $v \sin i$ of 10 km s^{-1} (Peterson et al. 1996).

3.2. Relationships between the Pulsational Properties and the Physical Properties

In this section, we focus on the relationships between physical properties (spectral types, periods, rotational velocities, and amplitudes) of the δ Sct stars. Similar efforts have been made previously. For example, Antonello et al. (1981) showed the amplitude–period–luminosity relation for LADS. Also Suarez et al. (2002) found a significant correlation between the oscillation amplitude and rotational velocity for δ Sct stars in OCs. As in the previous sections, we again removed the known binaries from all the relations.

As shown in Figure 6, there is a weak but certain relation between spectral type and period. The early-type stars tend to have shorter periods than the late types. This tendency can be explained as either an evolutionary effect or observational selection effect (Rodríguez et al. 2000). In both cases, other

[7] This star's spectral type is described as kF3hF7. The strength of the calcium II K absorption line and the Balmer lines are more like those of an F3 star and F7 star, respectively.

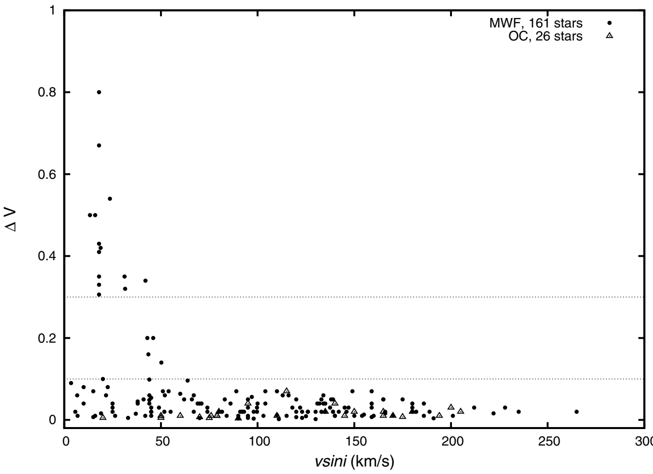

Figure 7. Relation between projected rotational velocity and full amplitude for the δ Sct stars. Field stars and OC member stars are indicated with dots and triangles, respectively. HADS are pulsators with both high-amplitude magnitude variations ($\Delta V \geqslant 0\overset{\text{m}}{.}3$) and slow rotational velocities ($v \sin i < 30$ km s^{-1}). In contrast, LADS have relatively rapid rotational velocities and low-amplitude variations ($\Delta V \leqslant 0\overset{\text{m}}{.}1$).

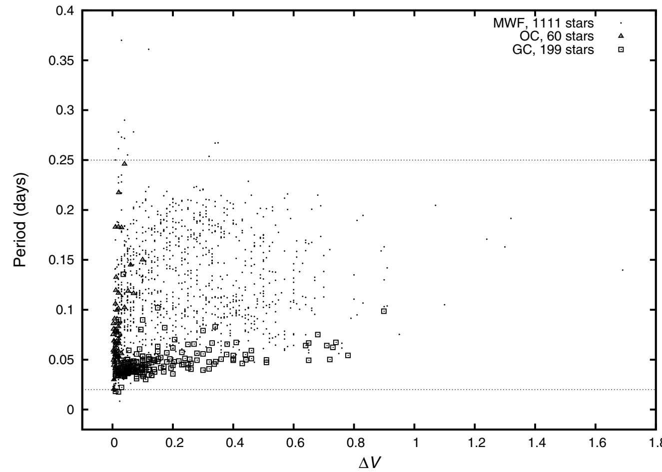

Figure 8. Relation between full amplitude and period for the δ Sct stars. Almost all MWF stars (small dots) are uniformly distributed between OC (open triangles) and GC (open squares) member stars. On the other hand, the two distributions of cluster member stars are remarkably different from the distribution of MWF stars.

stellar parameters have to be taken into account to derive a more reliable relation.

Figure 7 shows a clear distinction between HADS and LADS. As mentioned in Section 3.1, δ Sct stars with large amplitudes (at least $\Delta V \geqslant 0\overset{\text{m}}{.}3$) are regarded as HADS that rotate slowly with $v \sin i$ less than 30 km s^{-1} (Breger et al. 2007). On the other hand, LADS ($\Delta V \leqslant 0\overset{\text{m}}{.}1$) have a much greater range of $v \sin i$ including rapid rotational velocities (5.7–306 km s^{-1}). Also several δ Sct stars in the OCs show moderate or fast rotational velocities (20–205 km s^{-1}), which is consistent with $v \sin i$ values of LADS groups (Molenda-Zakowicz et al. 2009; Rodríguez et al. 2000). A similar trend was already found for 68 δ Sct stars by Solano & Fernley (1997), who showed that HADS tend to have lower rotation velocities, while LADS have a broader distribution in $v \sin i$. This empirical relation suggests that stellar rotation plays an important role in determining the size of the amplitudes of radial and non-radial modes (Breger 2007). Some δ Sct stars are known to have intermediate amplitudes between HADS and LADS ($0\overset{\text{m}}{.}1 < \Delta V < 0\overset{\text{m}}{.}3$). These stars are responsible for the astrophysical connection between HADS and LADS. For example, Breger et al. (2007) argued that EE Cam belongs to this transition population and Hintz & Schoonmaker (2009) also found that V873 Her, a medium-amplitude δ Sct, has similar properties to EE Cam as a member of the transition population. Other suspected transition stars (V0645 Her, V1162 Ori, V2109 Cyg, and DX Cet) also show amplitudes between $0\overset{\text{m}}{.}1$ and $0\overset{\text{m}}{.}2$.

Figure 8 tells us that there is no relation between amplitudes and periods for the entire field stars, while the distributions of cluster member stars are remarkably different. The latter stars show that long-period δ Sct stars seem to have more large amplitudes than short-period ones. From the amplitude–temperature–period relation, as Solano & Fernley (1997) pointed out, this relation can be explained by one hypothesis that the large amplitude stars are more evolved than the LADS.

4. X-RAY AND UV COUNTERPARTS OF THE δ Sct STARS

We cross-matched our catalog with several X-ray and UV catalogs in Table 4, and found 27 X-ray and 41 UV-only counterparts, respectively. It is known that some binary stars such as Algol-type binaries show X-ray emission (e.g., McGale et al. 1996; Stepien et al. 2001; Chen et al. 2006). In addition, X-ray/EUV emission is known to be a property of hot white dwarfs (March et al. 1997a, 1997b). The general properties of the X-ray and UV-only counterparts are summarized in Tables 5 and 6, respectively.

Among the X-ray counterparts of δ Sct stars, two Algol-type binaries (RZ Cas and R CMa) are known to have δ Sct companions (Rodríguez & Breger 2001). The X-ray origin of

Table 4
X-Ray, UV, and EUV Catalogs

ROSAT All-Sky Survey Bright Source Catalog (1RXS)	Voges et al. (1999)
ROSAT All-Sky Survey Faint Source Catalog (1RXS)	Voges et al. (2000)
BMW-*Chandra* Source Catalog (1BMC)	Romano et al. (2008)
XMM-Newton 2nd Incremental Source Catalog (2XMMi)	Watson et al. (2009b)
2RE Source Catalog of the *ROSAT* Wide Field Camera All-Sky Survey of Extreme-Ultraviolet Sources (2RE)	Pye et al. (1995)
Extreme Ultraviolet Explorer Source Catalog (*EUVE*)	Bowyer et al. (1996)
	Lampton et al. (1997)
	Christian et al. (1999)
Far Ultraviolet Spectroscopic Explorer Observation Log (*FUSE*)	FUSE Science Team (2005)
Midcourse Space Experiment Ultraviolet Point Source Catalog (*MSX*)	Newcomer et al. (2006)

Table 5
Properties of 19 X-Ray-only Sources and 8 X-Ray/UV Sources

R.A. (hh:mm:ss)	Decl. (dd:mm:ss)	Cross-matched ID	Source Catalog[a]	V	B	Frequency (cd^{-1})	ΔV (mmag)	Spectral Type	Type[b]	Designation[c]
00:09:10	+59:08:59	J000910.1+590903	*ROSAT* Bright	2.28	2.66	9.911	33	F2III	bm	*beta* Cas
		G117.5277−03.2775	*MSX*							
		HD432	*FUSE*							
01:12:08	+02:17:12	J011207.8+021710	2XMMi	11.899	12.569	5.663	160		unknown	
02:48:55	+69:38:03	J024854.7+693804	*ROSAT* Bright	6.26	6.411	62.112	20	A3V	EA	RZ Cas
		J024855.5+693803	2XMMi							
03:44:31	+32:06:22	J034430.6+320628	2XMMi	10.76	11.5	7.407	40	F0m:	unknown	V0705 Per
		034431.2+320621	BMW-*Chandra*							
03:47:24	+24:35:18	J034724.3+243513	*ROSAT* Bright	7.673	7.905	16.584	20	A4V	bm	V1228 Tau
		J034724.0+243517	2XMMi							
		G166.2980−23.1107	*MSX*							
		HD23628	*FUSE*							
04:28:39	+15:52:15	J042839.7+155217	2XMMi	3.4	3.579	13.228	20	A7III	bm	θ^2 Tau
05:15:24	+32:41:15	J051523.8+324107	*ROSAT* Bright	5.01	5.232	11.351	80	kA9hA9mF2	WD	KW Aur
		J0515+326	*EUVE*							
06:07:26	−76:55:36	J060725.1−765537	*ROSAT* Bright	9.63	10.222	4.998	230	F7V	unknown	
07:19:28	−16:23:43	J071928.0−162339	*ROSAT* Bright	5.7	6.046	21.277	10	kA8hF1mF2	EA	R CMa
		G230.6704−01.4057	*MSX*							
07:58:30	−60:37:46	J075830.9−603746	2XMMi	10.88			20	A8V	unknown	V0419 Car
		075830.9−603748	BMW-*Chandra*							
07:58:33	−60:49:26	J075833.3−604925	2XMMi	10.345	10.628		30	A3V	unknown	V0420 Car
		075833.3−604926	BMW-*Chandra*							
08:39:09	+19:35:33	J083909.1+193530	2XMMi	8.5	8.75	17.036	20	A9V	unknown	BS Cnc
08:51:32	+11:50:41	085132.1+115042	BMW-*Chandra*	12.25	12.52	18.832	20	F0	unknown	EW Cnc
12:07:05	−78:44:28	J120702.3−784428	*ROSAT* Faint	7.48	7.752	18.868	10	A9III/IV	unknown	EF Cha
		G300.6932−16.0626	*MSX*							
		HD105234	*FUSE*							
12:49:08	−41:12:26	J124908.8−411225	2XMMi	12.385	12.156	19.194	20	A3V	unknown	V1041 Cen
13:26:28	−47:31:02	J132627.6−473102	2XMMi	17.239	17.704	20.45	100		unknown	ω Cen - NV319
13:26:38	−47:27:38	132638.3−472741	BMW-*Chandra*	17.096		20.833	80		unknown	ω Cen - NV322
13:26:40	−47:29:11	132641.1−472911	BMW-*Chandra*	16.394	16.784	23.095	60		unknown	ω Cen - NV312
13:28:01	−47:23:19	J132801.5−472318	2XMMi	9.411	10.001		30	F8	unknown	V1030 Cen
14:43:04	−62:12:26	J144304.5−621226	2XMMi	7.4	7.559	28.249	10	A3V	unknown	BT Cir
16:14:40	+33:51:31	J161441.0+335125	*ROSAT* Bright	5.23	5.829	0.877	50	G1IV-V (k)	bm	TZ CrB
		J161440.7+335129	2XMMi							
		2RE J1614+335	*ROSAT*-2RE							
		J1614+338	*EUVE*							
16:41:38	+36:26:20	J164138.2+362627	2XMMi	17.12		15.314	250		unknown	M13 -V47
16:54:01	−41:53:24	J165402.2−415320	2XMMi	14.01		15.625	40		unknown	V1199 Sco
17:40:44	−53:40:42	174044.1−534039	BMW-*Chandra*	15.34	15.68	26.178	40		unknown	NGC 6397 - V11
19:39:54	−30:58:06	J193953.4−305805	2XMMi	17.09	17.45	24.39	29		unknown	M55 - V27
19:50:47	+08:52:06	J195047.0+085159	*ROSAT* Bright	0.76	0.981	15.773	4	A7Vn	bm	α Aql
		HD187642	*FUSE*							
21:26:26	+19:22:32	J212626.8+192224	*ROSAT* Bright	6.08	6.315	22.727	10	kA6hA9mF0	WD	IK Peg
		HD204188	*FUSE*							

Notes.
[a] *ROSAT* Bright: *ROSAT* All-Sky Survey Bright Source Catalog; *ROSAT* Faint: *ROSAT* All-Sky Survey Faint Source Catalog; 2XMMi: the *XMM-Newton* 2nd Incremental Source Catalog; BMW-*Chandra*: The Brera Multi-scale Wavelet *Chandra* Survey; *ROSAT*-2RE: the *ROSAT* Wide Field Camera all-sky survey of extreme-ultraviolet sources; *EUVE*: Second *Extreme Ultraviolet Explorer* Catalog; *FUSE*: *Far Ultraviolet Spectroscopic Explorer*; *MSX*: the *Midcourse Space Experiment* Ultraviolet Point Source Catalog.
[b] Spectral type.
[c] WD: white dwarf companion; EA: Algol-type variable star; bm: binary or multiple star; unknown: no specific information.
[d] GCVS designation.

these systems is thought to be chromospheric coronal activity of the subgiant star (Van den Oord & Mewe 1989; Singh et al. 1995). Another two of them are known as cataclysmic variable stars (CV), and were spectroscopically confirmed as a binary system that consists of a white dwarf and a δ Sct companion (McCook & Sion 1999). These two CVs have been studied by several authors (i.e., for J051523.8+324107 also known as 14 Aur or KW Aur, see Danziger & Dickens 1967; Fitch & Wisniewski 1979; Hodgkin et al. 1993, for J212626.8+192224 also known as IK Peg, see Kurtz 1979; Wonnacott et al. 1994). They also show EUV emission, which is one of the properties of hot white dwarf stars (Buckley 1995; March et al. 1997a, 1997b), and are selected as progenitors of type Ia supernovae (Parthasarathy et al. 2007).

One of the X-ray counterparts is a previously known very fast rotating star, Altair (α Aql), which is the brightest δ Sct star in

Table 6
Properties of 41 UV-only Sources

R.A. (hh:mm:ss)	Decl. (dd:mm:ss)	Cross-matched ID	Source Catalog[a]	V	B	Frequency (cd^{-1})	ΔV (mmag)	Spectral Type	Type[b]	Designation[c]
00:43:48	+42:16:56	G121.4228−20.5669	*MSX*	9.36	9.718	8.006	240	F3IV-V	bm	CC And
00:50:41	−50:59:13	G303.2241−66.1409	*MSX*	5.24	5.596	5.447	40	F3III	unknown	ρ Phe
02:10:25	+59:58:47	G132.6663−01.3911	*MSX*	6.66	6.994	9.158	48	kF0hF2mF2(III)	unknown	V0784 Cas
03:47:03	+24:49:12	G166.0675−22.9921	*MSX*	8.28	8.65	31.25	18	F0V	bm	V0534 Tau
04:16:39	−64:18:56	041639−641851	MSX04	7.97	8.266	14.925	20	F0III	unknown	TX Ret
05:38:05	−01:15:22	G205.4934−16.8532	*MSX*	9.92	10.24	10.309	20	F0Ve	unknown	V1247 Ori
06:14:08	+23:59:11	G187.4691+03.0744	*MSX*	7.53	7.885	5.316	50	F0	bm	PV Gem
06:19:37	+59:00:39	G155.5948+19.1163	*MSX*	4.44	4.472	15.385	300	A2V	bm	UZ Lyn
07:07:56	−04:40:40	G218.9778+01.5291	*MSX*	6.92	7.217	4.32	20	A9V	bm	V0752 Mon
07:11:23	−00:18:07	G215.4813+04.3013	*MSX*	5.44	5.75	10.0	50	F1IV	unknown	V0571 Mon
07:27:08	−17:51:53	G232.8306−00.4863	*MSX*	5.6	5.914	6.017	20	A9Vn	bm	NR CMa
08:27:36	−53:05:19	G269.2568−08.4423	*MSX*	5.08	5.336	14.286	10	F0III-IV	bm	GU Vel
08:58:52	−47:14:05	G267.7083−00.9048	*MSX*	5.17	5.438	15.385	20	F0V	bm	FZ Vel
09:11:07	−43:16:11	G266.2026+03.3494	*MSX*	7.88	8.194	4.292	20	A8-9III	unknown	MP Vel
09:56:54	−27:28:31	G261.8969+21.1682	*MSX*	6.32	6.493		10	A4V?	unknown	BF Ant
10:05:01	−56:53:53	G281.6679−01.0608	*MSX*	6.86	7.23	8.271	30	F2III/IV	unknown	V0336 Vel
10:05:13	−79:03:44	100512−790341	MSX04	7.32	7.568		80	A3/5III/IV	unknown	ER Cha
10:13:22	−51:13:59	G279.3845+04.2657	*MSX*	5.27	5.527	7.981	20	F0Vn	unknown	LW Vel
11:49:03	+14:34:19	HD102647	*FUSE*	2.14	2.23		25	A3V	bm	β Leo
12:02:06	+43:02:44	G151.8990+71.2009	*MSX*	5.22	5.503	25.0	20	kA4hA6mA7	unknown	DP UMa
12:23:47	+42:32:34	G141.2302+73.5894	*MSX*	6.03	6.396	8.598	70	F3IV	unknown	AI CVn
13:12:49	−61:32:42	G305.4777+01.2215	*MSX*	7.26	7.605	9.141	50	A9/F0III/IV	unknown	V0954 Cen
14:29:58	−56:07:52	G316.3983+04.1416	*MSX*	6.97	7.203	18.939	30	A6V	bm	V0853 Cen
15:01:02	−64:34:34	G316.2853−05.1186	*MSX*	6.56	6.858	6.329	70	A9/F0IV/V	unknown	BV Cir
15:18:34	+02:05:00	NGC 5904-ZNG1	*FUSE*	15.3		11.136	100		unknown	
15:42:44	+26:17:44	HD140436	*FUSE*	3.81	3.83	33.333	60	A0V	bm	γ CrB
16:27:51	−49:07:36	G334.9455−00.1925	*MSX*	13.51		16.807	3		unknown	
17:32:24	−34:16:46	G353.9809−00.4715	*MSX*	6.16	6.52	4.606	30	F2V	unknown	V0949 Sco
17:42:16	−32:31:24	G356.5669−01.2673	*MSX*	7.85	8.25	6.667	500	F0V	unknown	V0703 Sco
18:42:16	−09:03:09	G023.8330−02.0981	*MSX*	4.7	5.058	5.16	190	F2II-III	bm	δ Sct
18:59:51	+11:26:42	G044.0788+03.3517	*MSX*	7.72	8.183	6.2	56	F0	unknown	V1438 Aql
19:19:39	+12:22:29	G047.1398−00.5184	*MSX*	5.53	5.795	6.849	13	A9III	bm	V1208 Aql
19:42:49	+29:19:54	G064.6016+02.9162	*MSX*	6.54	6.877	11.364	20	F1III	unknown	V1276 Cyg
20:10:33	+26:54:14	G065.7093−03.5691	*MSX*	5.51	5.597	8.23	10	A2IV	unknown	
20:10:45	+26:44:36	201045+264437	MSX04	10.23	10.67	17.857	30	A7IV	unknown	V0381 Vul
20:14:14	+28:41:41	G067.6569−03.2692	*MSX*	5.19	5.381	5.316	16	A5Vn	unknown	NU Vul
20:56:35	−05:42:06	205635−054201	MSX04	13.285		12.903	450		unknown	
21:14:47	+38:02:43	G082.8535−07.4321	*MSX*	3.74	4.133	12.048	20	F2+ V	bm	τ Cyg
22:15:02	+57:02:37	G102.8657+00.3947	*MSX*	4.18	4.458	24.272	20	F0V(Sr)	bm	ϵ Cep
22:48:30	−10:33:20	G056.7989−56.6757	*MSX*	6.19	6.464	11.494	20	F1V	unknown	FM Aqr
23:28:25	−25:25:14	G033.4840−71.3326	*MSX*	6.9	7.06	8.482	20	A3	unknown	BS Scl

Notes.
[a] *ROSAT*-2RE: the *ROSAT* Wide Field Camera all-sky survey of extreme-ultraviolet sources; *EUVE*: Second Extreme Ultraviolet Explorer Catalog; *FUSE*: *Far Ultraviolet Spectroscopic Explorer*; *MSX*: the *Midcourse Space Experiment* Ultraviolet Point Source Catalog; MSX04: *MSX* UV Point Source Catalog.
[b] Spectral type.
[c] bm: binary or multiple star; unknown: no specific information.
[d] GCVS designation.

the sky (Buzasi et al. 2005). Even though Altair is inside the instability strip, no photometric variability was reported until the *Wide Field Infrared Explorer* satellite (Buzasi et al. 2005). The dominant source of X-ray emission is thought to be related to Altair's coronal activities (Robrade & Schmitt 2009).

Although most of the X-ray counterparts do not have information about their X-ray origin, they are all interesting objects for further observations and studies because of their rare characteristics which show δ Sct pulsation and X-ray emission at the same time. Specifically, five X-ray counterparts (J000910.1+590903, J034724.3+243513, J161441.0+335125, J195047.0+085159, and J120702.3−784428) seem very interesting objects because they also exhibit emission in optical and UV wavelength.

5. SUMMARY

We compiled a new catalog of 1578 δ Sct stars including the catalogs compiled by R2000, Rodríguez & López-González (2000), ASAS, ROSTE, TAOS, and several individual findings published after R2000. We highlight several key features and relationships between physical properties for the field and cluster member stars without companion objects. Most of the properties are similar to those previously reported by other studies (e.g., R2000; Rodríguez & Breger 2001). However, we also find indications of interesting correlations among pulsation and stellar parameters. For example, the relations between the full amplitude and period of the cluster member stars tell us that longer period δ Sct stars generally exhibit high-amplitude pulsations. The final catalog was cross-matched with several X-ray and UV catalogs; 27 X-ray and 41 UV-only counterparts were found. Among the X-ray and UV counterparts, there are two Algol-type eclipsing binaries, two CV stars, and several binary candidates. Further observations will reveal the origin of X-ray/UV emission and the effect of binarity on the pulsation characteristics. Our new catalog is accessible online at http://stardb.yonsei.ac.kr/DeltaScuti.

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