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Short-Period Variable Be Stars Discovered or Confirmed through Self-Correlation Analysis of *Hipparcos* Epoch Photometry

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ABSTRACT. We have surveyed 277 bright Be stars for short-period (0.2–2 day) photometric variability using self-correlation analysis of *Hipparcos* epoch photometry. This extends the work of Percy et al.; the methods are as described there. We report the discovery, timescale, and amplitude of short-period variability in: HD 7636 (V764 Cas), HD 11606 (V777 Cas), HD 13661 (V549 Per), HD 34921, HD 36408, HD 40978, HD 58343 (FW CMa), HD 63460 (o Pup), HD 88195 (17 Sex), HD 89353 (AG Ant, HR 4049), HD 129954 (CO Cir), HD 158220 (V862 Ara), HD 173219 (V947 Sct), and HD 187567 (V1339 Aql). We report the confirmation of short-period variability using an independent form of analysis in HD 52918 (19 Mon), HD 105382 (V863 Cen), HD 137387 (κ-1 Aps), HD 157832 (V750 Ara), and HD 163868 (V3984 Sgr). These include a β Cephei star (19 Mon), a Vega-type star (17 Sex), and a post-asymptotic giant branch B star (HR 4049). We find that short-period variability is more prevalent in early-B stars than in late-B stars. We have found no β Cephei type variables in our sample of Be stars, other than 19 Mon, which is apparently not a Be star.

1. INTRODUCTION

Be stars are nonsupergiant stars with effective temperatures of 10,000–30,000 K and that have shown hydrogen emission in their spectra on at least one occasion. The emission arises from an equatorial disk produced by the star's wind, by its larger-than-average rotation, and perhaps by other factors. Be stars are variable in brightness on different timescales, for different reasons. They vary on timescales of weeks to decades, because of the formation and dispersal of the disk. Some vary quasi-periodically on timescales from months to years, probably because of density waves within the disk. A few are close binaries and may vary because of the effects of their companions. Many vary on timescales of 0.2–2 days because of nonradial pulsation or possibly rotation. See Porter (2003) for an excellent recent review of Be stars in general; also, an important article by Rivinius et al. (2003) describes results of a new study of line profile variability in 27 Be stars (and reviews earlier work on this topic). Because of the continuing interest in the incidence, nature, and cause of the short-term variability, further study of this phenomenon is worthwhile.

Percy et al. (2002) have shown that self-correlation analysis can be useful for identifying short-period variability in *Hipparcos* photometry of Be stars and for determining the timescale and typical amplitude. We have now extended this work to survey a large number of Be stars in the *Hipparcos* archive.

2. SELF-CORRELATION ANALYSIS

Our algorithm works as follows: for all pairs of measurements, the difference in magnitude (Δmag) and the difference in time (Δt) are calculated. We plot Δmag against Δt, from zero up to some appropriate upper limit (which, if possible, should be a few times greater than the expected timescales but less than the total time span of the data). The Δmag are binned in Δt so that, if possible, there are at least a few values in each bin. The Δmag in each bin are then averaged. The average Δmag will be a minimum at multiples of τ. Each minimum can be used to estimate τ. The height of the maxima is a measure of the average amplitude of the variability. If the variability were perfectly periodic and the magnitudes had no error, then the minima would fall to zero; in fact, the height of the minima is determined by the average error of the magnitudes and by the degree of irregularity, if any. The persistence of the minima to large Δt is also determined by the degree of irregularity. Our method, by its nature, requires of the order of 10 or more Δmag in each bin. See Percy et al. (2002) for a more complete description of the method and of the nature and limitations of the *Hipparcos* epoch photometry. In particular, the effectiveness of self-correlation depends, in this case, on having a significant number of photometric measurements whose Δt are in the range of 0.2–2 or more days. The distribution of the *Hipparcos* measurements does not always conform to this requirement.

3. DATA AND METHOD

We compiled a more-or-less complete list of bright Be stars, starting with that of Yudin (2001) and supplementing it with other lists available to us. This list included 320 stars. For the majority of these stars, there was *Hipparcos* epoch photometry (this photometry is available from the *Hipparcos* Web site). In

TABLE 1
MEAN AMPLITUDE OF SHORT-PERIOD VARIABILITY

Spectral Type	*N*	Average	Median
B0	3	0.006	0.004
B0.5	3	0.005	0.005
B1	17	0.023	0.017
B1.5	8	0.011	0.010
B2	47	0.010	0.006
B2.5	13	0.009	0.005
B3	25	0.011	0.007
B4	12	0.015	0.012
B5	17	0.008	0.002
B6	13	0.010	0.003
B7	8	0.009	0.003
B8	12	0.003	0.001
B8.5	2	0.000	0.000
B9	5	0.001	0.000
B9.5	6	0.002	0.002

TABLE 2
SELF-CORRELATION ANALYSIS OF SHORT-PERIOD VARIABLE BE STARS

HIP	HD	Name	*V*	ΔH	*P* (days)
6027	7636	V764 Cas	6.89	0.005	0.6:
8980	11606	V777 Cas	7.02	0.030	0.6
10463	13661	V549 Per	7.86	0.020	0.4:
25114	34921	V420 Aur	7.45	0.015	0.8
25950	36408	…	5.46	0.030	0.9
28783	40978	V447 Aur	7.29	0.015	0.5
23971	52918	19 Mon	4.99	0.020	0.2
35951	58343	FW CMa	5.20	0.060	…
38070	63462	o Pup	4.50	0.010	0.75
49812	88195	17 Sex	5.90	0.003	1.5
50456	89353	AG Ant	5.53	0.004	0.5
59173	105382	V863 Cen	4.45	0.013	1.25
72438	129954	CO Cir	5.88	0.010	0.4
76013	137387	κ-1 Aps	5.49	0.020	0.6
85467	157832	V750 Ara	6.65	0.020	1.1
85751	158220	V862 Ara	5.99	0.030	1.15
88123	163868	V3984 Sgr	7.36	0.010	0.3
91946	173219	V947 Sct	7.88	0.025	4.0
97607	187567	V1339 Aql	6.48	0.004	0.7

NOTE.—Colons indicate uncertainty.

the present study, we have investigated 277 stars, in addition to those studied by Percy et al. (2002). We used the same form of the self-correlation method described by Percy et al. (2002).[1]

4. RESULTS

Of the stars that we analyze in this paper, 124 had no short-term Δt greater than 0.2 days, so it was not possible to say anything about their variability on timescales greater than about 0.4 days; 117 had Δt that provided some information about the possible presence and amplitude of variability on timescales of up to a day (and could be used for statistical purposes); and 33 had Δt that provided some information about the presence, amplitude, and timescale of short-term variation. Note that all amplitudes are in the wideband *Hipparcos* system and are designated by *H*.

This and the previous study (Percy et al. 2002) provided 189 stars for which we had some estimate of the average amplitude of short-term variability during the interval of the *Hipparcos* mission (1989–1993). Our sample is deficient in two respects: (1) It constitutes less than half of all Be stars that were observed; the others had no Δt that were long enough to provide information. We have no reason, however, to think that the 189 stars constitute a biased sample. (2) For many of the stars, the maximum Δt is only 0.4–0.5 days. If there was no obvious slope in the self-correlation diagram between 0.0 and this value, then we assumed the amplitude to be zero. However, we may have missed a few stars with longer periods (such as 2 days) and small amplitudes. With these limitations in mind, Table 1 lists the relationship between average and median amplitude and spectral type, and the number of stars in each spectral type bin.

Table 2 lists 19 stars for which the self-correlation results are reasonably well determined and/or interesting. Most of them are discussed individually below.

HD 7636 (HIP 6027, V764 Cas).—The self-correlation diagram is somewhat complex; it shows minima at 0.7, 1.1, and 1.65 days. This star shows quasi-cyclic variations of $\Delta H = 0.08$ on a timescale of 500 days (Hubert & Floquet 1998).

HD 11606 (HIP 8980, V777 Cas).—This star shows recurrent short-lived outbursts of $\Delta H = 0.15$ on a timescale of 50–100 days. The amplitude of the short-term variability is at least 0.03.

HD 13661 (HIP 10463, V549 Per).—The self-correlation diagram is somewhat complex; there are minima at 0.4 and 0.8 days.

HD 34921 (HIP 25114, V420 Aur).—This star is a high-mass X-ray binary (Polcaro et al. 1990), presumably with a compact companion.

HD 36408 (HIP 25950, HR 1847).—Van den Ancker, de Winter, & Tjin A Djie (1998) observed this star as part of a study of Herbig Ae/Be stars but listed it as "lacking evidence for circumstellar dust," which suggests that it is a classical Be star (see Fig. 1).

HD 40978 (HIP 28783, V447 Aur).—Koen & Eyer (2002) claim a period of 0.09 days, but this is probably an artifact of the time distribution of the *Hipparcos* photometry. There is no evidence for such a period in the self-correlation diagram (Fig. 2); there are minima at 0.5, 1.0, 1.5, 2.0, 2.5, and 3.0 days, clearly indicating a timescale of 0.5 days. Note the rising self-correlation diagram, which indicates additional variability on a timescale of days to weeks.

HD 52918 (HIP 33971, 19 Mon).—This star is a well-known

[1] The software is freely available at http://www.astro.utoronto.ca/~percy/index.html.

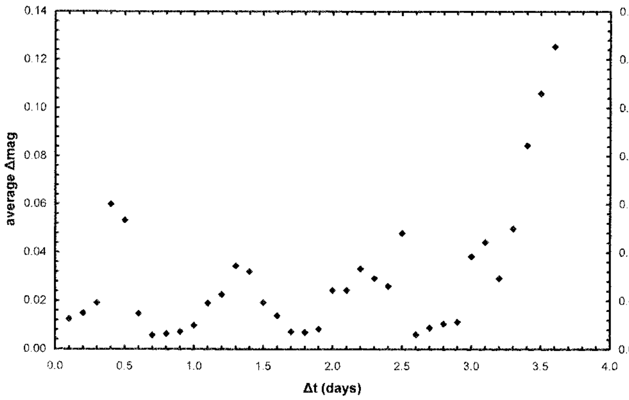

FIG. 1.—Self-correlation diagram for HD 36408 (HIP 25950, HR 1847). Note the minima at multiples of 0.9 days, indicating that this is a characteristic timescale of the variability. The base level of the minima, due to observational error, is about 0.005 mag. The points at Δt greater than 3 days are not significant because there are too few Δmag values in each bin.

β Cephei star with a period of 0.191 days. The self-correlation diagram confirms this result. According to Balona et al. (2002), there is no evidence that this star is or was a Be star

HD 58343 (HIP 35951, FW CMa).—The unusual self-correlation diagram of this star (Fig. 3), rising linearly with Δt to 4 days or more, is due to the fact that it was observed by *Hipparcos* continuously for 4 days and shows significant photometric activity on that timescale.

HD 63462 (HIP 38070, o Pup).—Barrera, Mennickent, & Vogt (1991) found large photometric changes, with no periodicity. The self-correlation diagram is complex.

HD 88195 (HIP 49812, 17 Sex).—This star is classified A1V, a Vega type star with a β Pictoris type gas disk. The amplitude of the self-correlation diagram (0.003) is small but appears real (Fig. 4). However, the first minimum is normally at the same level as Δmag at $\Delta t = 0$, so the interpretation of this star is not clear. Adelman (2001) lists this star among the "least variable stars" in the *Hipparcos* database, with a standard error of 0.0004. He considers any apparent variability to be duplicity induced; the star is a close visual binary.

HD 89353 (HIP 50456, HR 4049, AG Ant).—This star is considered to be the prototype of a group of post-asymptotic giant branch (AGB) stars that are members of close binary systems and that show a high degree of metal depletion, probably the result of dust condensation during their AGB life (Van Winckel et al. 1995). This star finds itself among the B-type stars as it contracts toward the white dwarf region. The amplitude of the self-correlation diagram is small, but the mini-

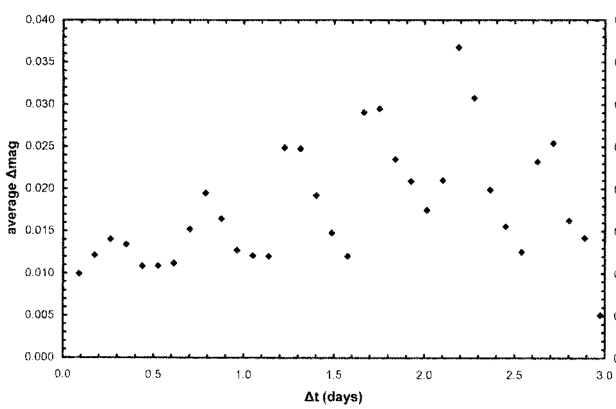

FIG. 2.—Self-correlation diagram for HD 40978 (HIP 28783, V447 Aur). Note the minima at multiples of 0.5 days, indicating that this is a characteristic timescale of the variability. The base level of the minima, due to observational error, is about 0.010 mag. The points at Δt greater than 2.5 days are not significant because there are too few Δmag values in each bin. The rising trend in the maxima may be due to additional variability timescales of several days or more.

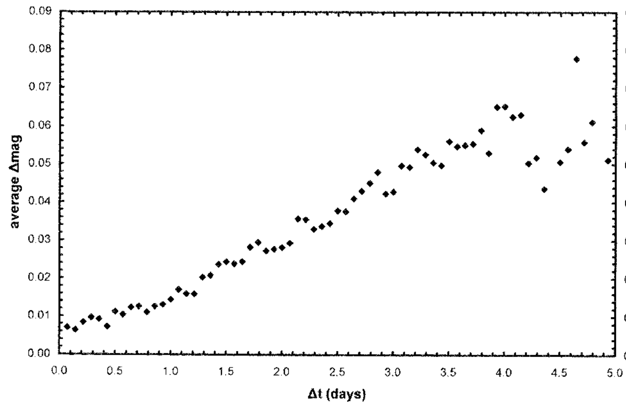

FIG. 3.—Self-correlation diagram for HD 58343 (HIP 35951, FW CMa). The rising trend is almost entirely due to one 4 day monitoring of the star by *Hipparcos*, during which time the star varied significantly. This suggests that statistically, this is an active star. The points at Δt greater than 4 days are not significant because there are too few Δmag values in each bin.

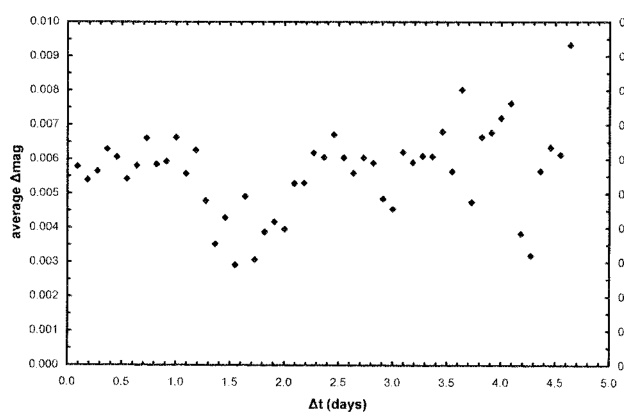

FIG. 4.—Self-correlation diagram for HD 88195 (HIP 49812, 17 Sex). There is a shallow minimum at 1.5 days, but it is below the apparent base level of the minima of 0.006 mag, and there is no clear minimum at 3 days, so its significance is not clear.

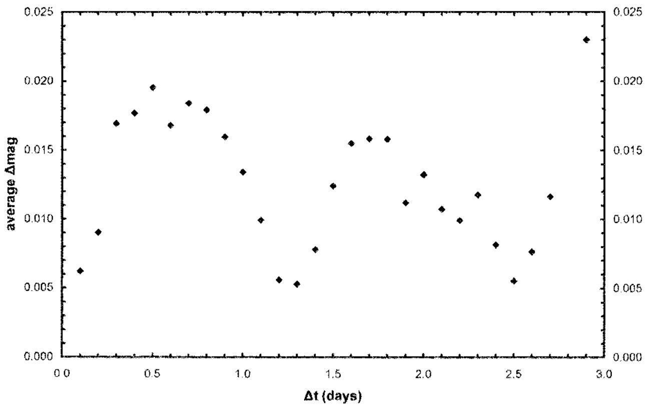

FIG. 5.—Self-correlation diagram for HD 105382 (HIP 59173, V863 Cen). Note the minima at 1.25 and 2.5 days, indicating a characteristic timescale of 1.25 days for the variability. The base level of the minima, due to observational error, is about 0.005 mag.

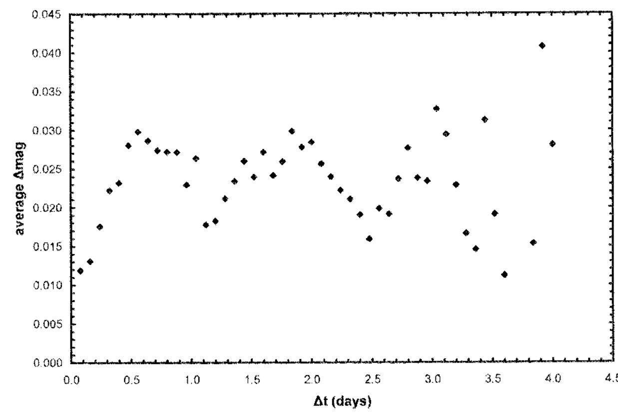

FIG. 6.—Self-correlation diagram for HD 157832 (HIP 85467, V750 Ara). Note the minima at multiples of 1.2 days, indicating that this is a characteristic timescale for the variability. The base level of the minima, due to observational error, is about 0.012 mag. The points at Δt greater than 3 days are not significant because there are too few Δmag values in each bin.

mum at 0.5 days is well defined. The presence of short-period variability in this star suggests that the short-term variability depends on the physical properties of the star and not on the star's evolutionary history.

HD 105382 (HIP 59173, V863 Cen).—This star is known to have a period of about 1.29 days. The self-correlation diagram (Fig. 5) is consistent with this result; there are minima at 1.25 and 2.5 days. Barrera et al. (1991) obtained a period of 0.41 days (the light curve could be "triple wave"). Briquet, Aerts, & De Cat (2001) question whether this is a Be star and state that neither a rotational nor a pulsational model explains the variability satisfactorily.

HD 129954 (HIP 72438, CO Cir).—This star shows quasi-cyclic variations of $\Delta H = 0.10$ on a timescale of 900 days (Hubert & Floquet 1998). The self-correlation diagram shows minima at 0.4, 0.8, 1.2, and 1.6 days.

HD 137387 (HIP 76013, κ-1 Aps).—Cuypers, Balona, & Marang (1989) found a period of 1.238 days with a double-wave light curve; Barrera et al. (1991) found a photometric period of 0.53 days. The self-correlation diagram is consistent with both of these results if the light curve is a double wave. This star shows quasi-cyclic variations on a timescale greater than 1200 days (Hubert & Floquet 1998).

HD 157832 (HIP 85467, V750 Ara).—Hubert & Floquet (1998) found a period of 1.104 days using a Fourier/CLEAN analysis. The self-correlation diagram (Fig. 6) is consistent with this result; there are minima at about 1.2, 2.4, and 3.6 days.

HD163868 (HIP 88123, V3984 Sgr).—The unusual self-correlation diagram of this star (Fig. 7), rising linearly with Δt to 4 days or more, is due to the fact that the star was monitored continuously for 4 days, and it is very active on that timescale. Woodward (1975) found possible variations on a timescale of several hours (0.3–0.5 days, from inspection of her data). The self-correlation diagram is consistent with this result in the sense that there are minima at 0.3, 0.6, 0.9, and 1.2 days superimposed on the upward linear trend, suggesting a timescale of 0.3 days.

HD 173219 (HIP 91946, V947 Sct).—Sterken, Vogt, & Mennickent (1996) have studied the long-term photometric variations in this star. It is a spectroscopic binary with a period of 58.395 days.

HD 187567 (HIP 97607, V1339 Aql).—This star shows monotonic, long-term variations in brightness (Hubert & Floquet 1998); otherwise, despite its significant variability ($V = 6.33$–6.52, according to SIMBAD), this star has been rather neglected. The self-correlation diagram shows minima at 0.7, 1.4, 2.1, and 2.9 days, indicating a timescale of 0.7 days.

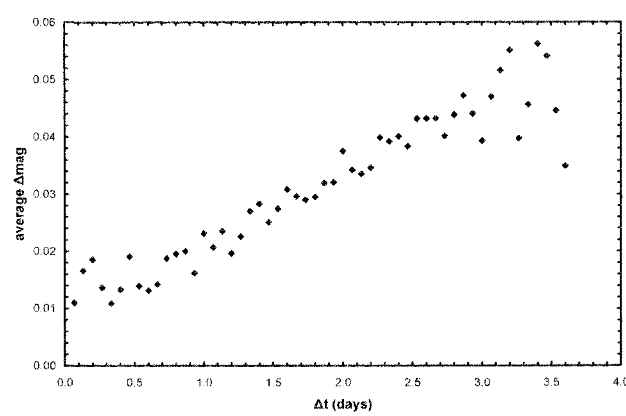

FIG. 7.—Self-correlation diagram for HD 163868 (HIP 88123, V3984 Sgr). As with FW CMa, the rising trend is almost entirely due to one 4 day monitoring of the star by *Hipparcos*, during which time the star varied significantly. This suggests that statistically, this is an active star. Superimposed on the rising trend, there are also minima at multiples of 0.3 days, indicating that this is a characteristic timescale for the variability. The points at Δt greater than 3 days are not significant because there are too few Δmag in each bin.

5. DISCUSSION

Subject to the limitations of our sample and the *Hipparcos* observations, we can infer from the average and median levels of short-term variability given in Table 1 that the level of short-term variability is greater for the early-B stars than for the late-B stars. This is consistent with the results of Stagg (1987), who found from a large-scale photometric survey that the level of short- and intermediate-term variability was greater in B0–B5-type Be stars than in B6–B9-type Be stars, at a 97%–99% level of significance. It is also consistent with the recent survey of line profile variability described by Rivinius et al. (2003). Assuming that the line profile variability and the photometric variability are due to low-order nonradial pulsation (Rivinius et al. 2003), then this result presumably reflects the dependence of the pulsation mechanism on temperature.

We have discovered 14 candidate short-period variable Be stars. These should be observed intensively both photometrically and spectroscopically to confirm the variability and to determine the variability properties in detail. One of the advantages of any survey, such as this one, is to identify stars that deserve further study. The study of individual stars can provide important clues to the nature of the Be phenomenon. For instance, it may be possible to demonstrate that the beating of multiple modes can produce a total amplitude that is large enough to facilitate the ejection of the disk.

β Cephei stars are early-B stars that pulsate radially with periods of 0.1–0.3 days, with small amplitudes. A substantial fraction of Be stars have spectral types that, aside from the emission lines, are similar to those of β Cephei stars, namely B0.5–2 III–IV. β Cephei stars can be identified through self-correlation analysis of *Hipparcos* epoch photometry (Percy, Coulter, & Mohammed 2003). The problems of doing so are not the lack of Δt greater than 0.2 days, but with the specific observing schedule of the satellite such that there are no Δt between 0.0143 and 0.0746 days, 0.1032 and 0.1635 days, etc. Nevertheless, we can say that in our sample, no stars were found with β Cephei–like variability with Δmag greater than 0.01, except for 19 Mon, which, according to Balona et al. (2002) is not a Be star. The other possible exception is V3984 Sgr, with a possible period of 0.3 days; a double-wave light curve with a period of 0.6 days is also possible. It is not immediately obvious why β Cephei pulsation should not be found in Be stars.

The timescales that we derive from self-correlation are generally in agreement with timescales derived by Fourier analysis or by inspection of light curves. Many short-period Be stars have double-wave or even triple-wave light curves. This sometimes makes it difficult to know whether the self-correlation period is the true period or half or a third of the true period. Self-correlation analysis is not well suited to stars that are multiperiodic.

The results for FW CMa, V3984 Sgr, and QR Vul (Percy et al. 2002) suggest, however, that it might be useful to apply this method to databases that explore the longer term variability of Be stars, such as our database (Percy & Bakos 2001) and that of our collaborators in the Czech Republic and Croatia (Pavlovski et al. 1997), in order to look at variability on timescales of 3–30 days. We do not expect to find cyclic variability on these timescales, but the method may possibly be useful in providing an average "profile" (as represented by the self-correlation diagram) of the timescale and amplitude of the variability. For instance, some Be stars can be described as "photometrically active"; the self-correlation may be able to quantify that description.

6. CONCLUSIONS AND FUTURE WORK

Self-correlation has proven to be a useful way of confirming and discovering short-period variable Be stars in the *Hipparcos* epoch photometry database, despite the limitations of the method and the data. Our method of analysis does not solve the problem of the cause of the short-term variability, but it does identify stars that should be observed by a variety of techniques in more detail. These include several "classical" Be stars and also a few stars that are not classical Be stars but have similar properties. We have now applied the self-correlation method to almost all of the Be stars in the database to look for variability on timescales of 0.2–2 days.

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