SPACE OBSERVATIONS OF CHEMICALLY PECULIAR AND RELATED NORMAL STARS

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ABSTRACT. Progress in the spectroscopic study of CP stars and related sharp-lined normal stars from the IUE is briefly reviewed as a preamble to a discussion of the potential for research with the Hubble Space Telescope. The substantial gains in spectral resolution, signal-to-noise ratio and photometric accuracy that will be realized with the High Resolution Spectrograph on the HST will dramatically increase our ability to disentangle the complex ultraviolet spectra of these stars and to carry out accurate quantitative analyses.

1. INTRODUCTION

A decade ago at IAU Colloquium Number 32 in Vienna, Leckrone (1975) reviewed the properties of CP stars as observed from space. At that time the observational data were limited almost entirely to broad-band photometry and intermediate-band spectrophotometry in the wavelength interval 1100Å to 3000Å, which revealed the flux deficiencies of the CP stars in the ultraviolet, and which explained the complex photometric variations observed in the optical region as being due to variable backwarming. Since the time of that meeting a great deal of UV spectroscopic work has been carried out on CP stars, primarily with the International Ultraviolet Explorer (IUE). The extended lifetime of the IUE has allowed UV spectroscopy to advance from qualitative surveys to detailed quantitative abundance analyses. Results obtained by several groups have been reported in the literature for B, Al, Si, Cu, Ga, Sb, Pt, Hg, and Bi (Jacobs and Dworetsky 1981,1982; Dworetsky et al. 1984; Leckrone 1980,1981,1984; Sadakane et al. 1983,1985). In each case the information obtained from space has provided a test of the predictions of diffusion theory, has led to the identification of new anomalous species or has supported and strengthened previous ground-based work. We are only just beginning to reap the harvest of information from the IUE, as I hope to show in this discussion and we are on the threshold of a new era of quantitative accuracy, resolution and sensitivity which will be provided by the Hubble Space Telescope (HST).

C. R. Cowley et al (eds.), Upper Main Sequence Stars with Anomalous Abundances, 109–119.

2. COMPREHENSIVE ABUNDANCE ANALYSES WITH IUE AND OPTICAL DATA

Adelman and Leckrone have undertaken a long-term project to establish fundamental abundances for as many species as possible, beginning with the iron peak elements, in a selected group of CP and normal, sharp-lined B and A stars. The approach is to combine high quality, composited IUE spectra (Adelman and Leckrone 1985) with high signal-to-noise optical spectra in fully self-consistent abundance analyses. Since our data encompass the wavelength range from about 1250Å to about 6000Å, we can cover a larger fraction of the periodic table, a wider range of excitation and ionization states, and for many species a statistically more significant sample of lines than can be achieved from optical data alone. The ultraviolet spectra not only make available low excitation or resonance lines of many important species but also in some cases provide lines whose oscillator strengths and damping constants are more accurately determined than those of their counterparts at optical wavelengths. On the other hand all such analyses are currently limited by the high line density of ultraviolet spectra, the lack of accurate atomic data for most of the contaminate blending lines and the rather low resolution ($\lambda/\Delta\lambda \simeq 15000$) and signal-to-noise ratio (<30) of the IUE data. We are still in the process of learning how best to ameliorate these problems in the IUE data. In the long term the observational problems will be greatly diminished by use of the High Resolution Spectrograph (HRS) on the HST.

TABLE 1

IUE ABUNDANCE PROGRAM STARS

Star	Type	Teff	V Sin i
θ Leo	A2 V	9250	20
o Peg	A1 V(Am?)	9625	12
ν Cap	B9.5 V	10250	17
134 Tau	B9 IV	10825	22
21 Aql	B8 III	13000	19
π Cet	B7 V	13150	18
ι CrB	HgMn	11380	3
κ Cnc	HgMn	13300	6
HD109995	A2(FHB)	8100	17

The stars currently being analysed in the Adelman and Leckrone abundance program are listed in Table 1. They were selected both for their low values of v sin i and also because a substantial amount of work on their optical spectra has already been completed. IUE data for all of these stars have been obtained and the data reduction, involving the co-addition of many spectra so as to reduce both random and fixed-pattern noise, is now complete. Our intent is to continue to update the abundances derived for these stars as improved observational or atomic data become available, thus establishing and maintaining them as reference standards.

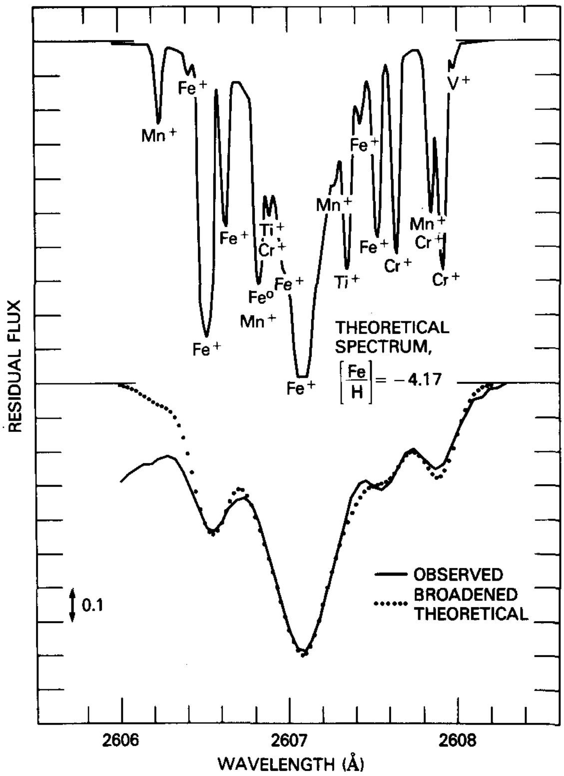

Figure 1. Spectral synthesis of the resonance line FeII λ2607 in o Peg. Top - theoretical spectrum with log[N(Fe)/N(H)] = -4.17. Bottom - IUE observation (solid curve) compared to theoretical spectrum, suitably broadened with rotation and instrument function.

The analyses have begun with iron, because its abundance is reasonably well established from the optical data alone. It thus provides a good opportunity to compare abundances obtained from both ultraviolet and optical regions for consistency. The top section of Figure 1 illustrates the computed synthetic spectrum of the resonance line, FeII(1) λ2607.086, in o Pegasi. Note the large number of blending lines. The line lists and log gf values of Kurucz and Peytremann (1975) and Kurucz (1981) were used initially for these blending lines. But it is well known that these data contain systematic errors, and it is necessary to artificially modify the semi-empirical log gf values of some of the blending lines in order to achieve a good fit to the observations. This procedure, which is discussed in detail in Leckrone (1981) for example, is bounded by the requirement that the adopted mix of log gf values for the blending lines must work for all of the stars we analyse. As long as the primary line being synthesized (in this case FeII λ2607) is the dominate member of the blend, rather large errors in the calculated strengths and positions of the blending contaminates can be incurred without seriously affecting the derived abundance. Errors will typically be less than 0.1 dex, even if we ignore a major blending contributor. In the computation illustrated in Figure 1, the log gf value used for the FeII resonance line is taken from a new critical compilation by Martin et al. (1986). Its uncertainty of approximately 10% is substantially lower than that of any currently available log gf values for FeII lines in the optical region. The lower part of Figure 1 shows this synthetic spectrum, convolved with the slit broadening function of the IUE spectrograph and rotated up to 12 km/s, compared to the line as observed with the IUE. The fit is reasonably good for an iron abundance log[N(Fe)/N(H)] = -4.17.

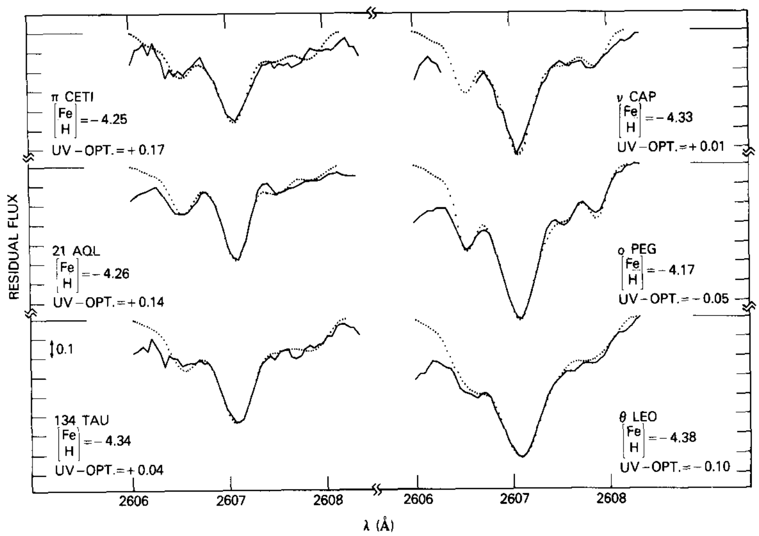

Figure 2. Spectral syntheses of FeII λ2607 in six normal stars. Solid curves are features observed with IUE; dotted curves are suitably broadened theoretical profiles.

Figure 2 illustrates the syntheses of FeII(1) λ2607 for the six normal stars included in Adelman and Leckrone's program. Using the procedures illustrated in detail in Figure 1, one obtains a good fit to all the observations. The preliminary abundances derived from this single ultraviolet resonance line of FeII are compared to the iron abundances derived from optical region observations of the same stars in Table 2. The generally good agreement between optical and ultraviolet values in the normal stars (top section of Table 2) is encouraging and gives us confidence to proceed with the analyses of numerous ultroviolet lines. There does appear to be a small systematic effect, which we do not yet understand, in that the optical abundances for the hotter stars tend to be lower than those derived from this single UV line. It will be of interest to see if this effect persists as we analyse additional Fe lines and as we continue to refine our data analysis techniques (for example, in the way we locate the continuum). We intend to complete similar analyses for about twelve additional ultraviolet FeII lines which have log gf values of quality B or B+ on the U.S. National Bureau of Standards scale of accuracy, i.e. with uncertainties around 10%. In addition we have good IUE data for about 25 other FeII lines, whose transition probabilities are less well known, for which astrophysical f-values could be derived. We are interested not only in accurate absolute abundances, but, for the normal stars, in the possible variations in abundances from star-to-star. After iron we will proceed to Mn, Co, Ni and other elements of the iron peak and ultimately to as much of the periodic table as possible.

TABLE 2

PRELIMINARY IRON ABUNDANCE RESULTS

Star	Optical	λ2607	UV - Optical
π Cet	-4.42	-4.25	+0.17
21 Aql	-4.40	-4.26	+0.14
134 Tau	-4.38	-4.34	+0.04
ν Cap	-4.34	-4.33	+0.01
o Peg	-4.12	-4.17	-0.05
θ Leo	-4.28	-4.38	-0.10
Average	-4.32±0.11	-4.29±0.08	σ = 0.11
Sun	-4.37		
ι CrB	-4.20	-4.05	+0.15
κ Cnc	-4.47	-4.10	+0.37

3. PROSPECTS FOR RESEARCH WITH THE HUBBLE SPACE TELESCOPE

It is evident from the work done by numerous people on the IUE spectra of CP and related normal stars that a rich store of information about the nature and origin of chemical anomalies resides in the complex ultraviolet spectra of these stars. The best tool for accurate quantitative studies of this region will undoubtedly be the High Resolution Spectrograph (HRS) on the Hubble Space Telescope (HST), to be launched by NASA's Space Shuttle during the latter half of 1986. The HST will be maintained and repaired in orbit by Shuttle crew members over its lifetime of at least fifteen years. Its instruments can be replaced with even more sophisticated devices as time goes on. Recently several candidate second generation HST instruments were selected for study, including an echelle spectrograph with a two-dimensional, photon-counting imaging detector (the STIS or Space Telescope Imaging Spectrograph), which will allow simultaneous observations over a much wider wavelength interval than that covered by the HRS. Both the HRS and the STIS will have substantially wider dynamic ranges and lower levels of background noise than does the IUE.

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In addition to spectroscopy the HST will provide other important capabilities for the study of CP stars. The basic characteristics of the scientific instruments which will be on board the HST at launch are summarized in Table 3. The High Speed Photometer (HSP), which is capable of accurate photometry in time bins as short as 10 μsec, might well be applied to the study of rapid variability throughout the ultraviolet and optical bands. The search for CP stars in clusters could be simplified by the high angular resolution (0.1 arcseconds) and the large selection of UV and optical filters in the two cameras. With regard to the HRS it is important to note that the highest resolving power ($\lambda/\Delta\lambda \approx 95000$) is obtained with an echelle grating which introduces a significant amount of scattered light. The scattered light background can be measured and subtracted out but at the expense of longer exposure times. On the other hand the intermediate 25000 resolving power, obtained in first order, offers almost twice the resolution of the IUE and a superbly dark background. Thus one must exercise judgement as to whether the highest possible signal-to-noise ratio or the highest possible resolution is needed for a given observation. Note that the resolving power in the 25000 mode might be improved to about 50000 by deconvolving the instrumental broadening function from data with a sufficiently high signal-to-noise. The detectors in the HRS are linear diode arrays (Digicons). This limits the width of the spectral interval that can be measured in a single exposure to about 5 to 18 Å in the 95000 mode and to about 26 to 48 Å in the 25000 mode.

TABLE 3

HUBBLE SPACE TELESCOPE SCIENTIFIC INSTRUMENTS

	WAVELENGTH RANGE (A)	FIELD OF VIEW (ARCSEC)	ANGULAR RESOLUTION (ARCSEC)	SPECTRAL RESOLVING POWER	MINIMUM ACCUMULATION TIME (MSEC)	"LIMITING MAGNITUDE" (m_V)
WIDE FIELD AND PLANETARY CAMERA	1150-11500	70-160	0.1-0.2	FILTERS	100	28
FAINT OBJECT CAMERA	1150-7000	<44	<0.1	FILTERS	50	28
HIGH RESOLUTION SPECTROGRAPH	1100-3200	0.25-2.0	N/A	95000 25000 2500	200	12-16
FAINT OBJECT SPECTROGRAPH	1150-8000	0.1-4.0	N/A	1200 200	10	23-26
HIGH SPEED PHOTOMETER	1150-9000	0.4-1.0	N/A	FILTERS	0.01	24
FINE GUIDANCE SENSOR ASTROMETER	4670-7000	≅500	0.002	FILTERS	N/A	19

In the following discussion I use the example of the HgII resonance line at 1942 Å, which was the subject of my recent paper (Leckrone 1984), to illustrate the potential applications of the HRS to the study of the

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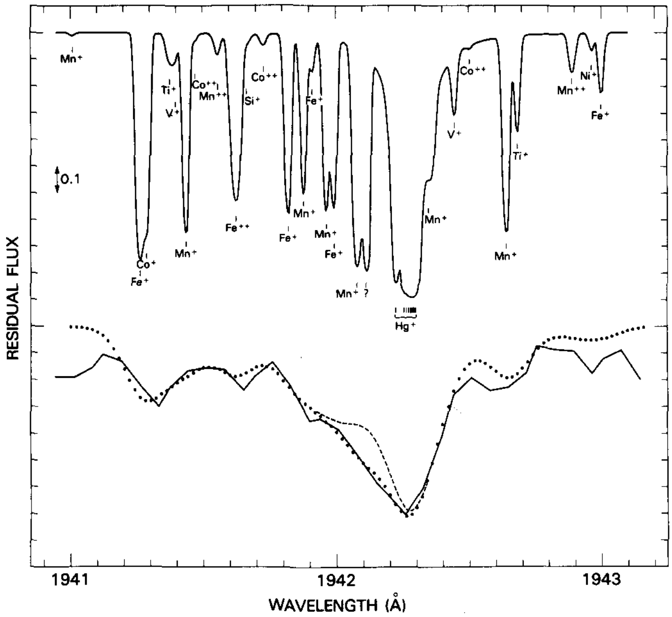

Figure 3. Spectral synthesis of the HgII λ1942 resonance line in ι CrB. Top - theoretical spectrum with log[N(Hg)/N(H)] = -6.1. Bottom - IUE observation (solid curve) compared to suitably broadened theoretical computation (dots) and to a theoretical computation from which an unidentified blending feature (question mark in upper figure) has been omitted (dashed curve).

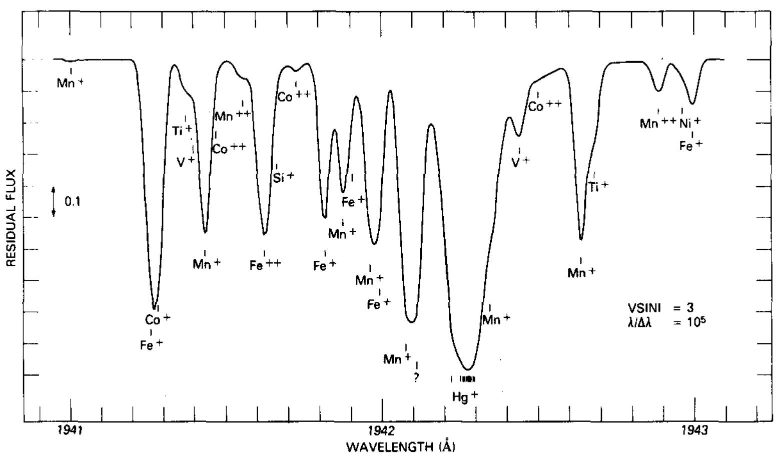

Figure 4. Theoretical spectrum from Figure 3 broadened with the expected instrumental function for the highest resolution mode of the High Resolution Spectrograph.

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ultraviolet spectra of the sharpest-lined stars, many of which are included in the various classes of chemically peculiar stars. Why is one interested in the HgII resonance lines? Prior to the IUE the Hg anomaly rested entirely on observations of HgII λ3984, plus the very weak HgI λ4358 line seen in only a few stars. Figure 9 of Leckrone (1984) shows computed curves of growth for λ3984 as a function of isotopic mix parameter, q, effective temperature and microturbulent velocity, V_t. It is clear that the strength of λ3984 is extremely sensitive to the choice of q and V_t. Small errors in these parameters will produce large errors in the Hg abundance derived from this line. This is the cause of much of the large star-to-star scatter in Hg abundances found in the literature. In contrast, as is shown in Figure 3 of Leckrone (1984), the resonance line of HgII at 1942.275 Å is insensitive to all three parameters and is only slightly sensitive to the adopted value of the damping constant (it is dominated by radiation damping, which is easily calculated). Thus, this line should yield accurate abundances, provided the problems of line blending discussed previously can be overcome. The detailed synthesis of λ1942 in IUE observations of the HgMn star ι CrB is shown in Figure 3. The technique used is identical to that discussed earlier for the FeII lines. That is the Kurucz-Peytremann log gf values of the contaminate blending lines had to be adjusted to achieve an acceptable fit to the observations in all the stars considered. Also in this case an extra blending line of unknown identity (I assumed TiII) had to be added to the blend to explain the asymmetry of the line core on its short wavelength side. This is consistent with the findings of Cowley and Johannson (in this colloquium) that there are a significant number of missing lines in the available line lists. At the bottom of Figure 3 is this same synthetic spectrum, convolved with rotational and IUE instrumental broadening functions, and overlaid on the observed feature in ι CrB. The dashed line shows the theoretical spectrum without the addition of the unknown blending contaminate, for comparison. Figure 4 illustrates the synthetic spectrum from Figure 3 convolved with the 3 km/s rotational broadening function and with the instrumental broadening function of the HRS in the 95000 resolving power mode. Most of the blending lines, whose identities we could only guess in the IUE spectra are now resolved, and even some of the weak features show up as partially resolved bumps or shoulders on the stronger lines. In addition we are more likely to accurately locate the line-free continuum in such high resolution observations (this is a difficult but not insurmountable problem in the IUE spectra). The signal-to-noise ratio in HRS observations of this sort will be limited only by the length of time one chooses to devote to counting photons, but in a realistic situation would likely be at least a factor of two better than in the best co-added IUE spectra. The problem then becomes one of adequately supporting the atomic physicists who are interested in providing the accurate atomic data needed to do justice to such observations.

In Figure 5 I have focused on an approximately 1 Å spectral interval around λ1942.275 and have performed the computation of the synthetic spectrum for two extreme values of the isotopic mix parameter, q. The value q = -0.1 corresponds to a nearly terrestrial mix (as in the HgMn star μ Lep, for example), while the value q = +3.0 corresponds to an extreme isotopic anomaly (almost pure Hg^{204}) as is found in χ Lup. At this resolving power and with good signal-to-noise one will be able to discriminate to some degree the isotopic structure of this Hg line to compare it to previously reported results for λ3984.

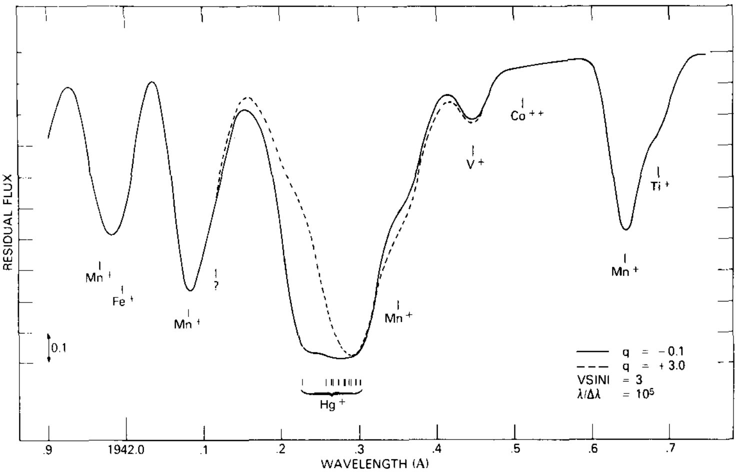

Figure 5. Theoretical computations of HgII λ1942 for two extreme values of the isotopic mix parameter, q, broadened to v sin i = 3 km/s and degraded to the highest resolution of the HRS.

4. EARLY OBSERVATIONS OF CP STARS WITH THE HST

The first observations of CP and related normal stars with the HST will be those I carry out as a member of the High Resolution Spectrograph Team. My program is made up of eight separate observational objectives, which focus on non-magnetic HgMn stars, a field horizontal branch star, and normal sharp-lined B and A main-sequence stars. The selection of objectives reflects my own judgement as to what scientific questions will be most amenable to immediate attack with the new observational capabilities of the HRS, as well as my own historical research interests. Certainly the magnetic CP stars, the Am stars, the stars with anomalous He lines, etc., will also provide fruitful research opportunities with the HRS and the other HST instruments. In the following discussion, I summarize my observational programs both to give an idea of the types of research one might undertake with the HRS and to point out the opportunity that is now being provided to astronomers from all over the world to submit proposals to observe with the HST. My programs are constrained to about 30 hours of observing time spread out over 2.5 years - sufficient only to scratch the surface of the important research to be done. The data obtained will be protected for one year after the completion of the observations, after which time they will become part of the archives of HST data accessible to the general community.

The eight major parts of my observing program are listed below. Table 4 lists the target stars associated with these objectives.

Part 1. - Survey BII λ1362 resonance line at λ/Δλ ≃ 95000 in HgMn and normal stars to establish B abundance trends.

Part 2. - Establish Hg abundance in normal stars based on observations of resonance lines at λ/Δλ ≃ 95000.

Part 3. - Study the systematic behavior of UV lines of HgI, HgII and HgIII and derive accurate Hg abundances in a wide range of Hg-rich stars at λ/Δλ ≃ 95000.

Part 4. - Explore odd-even abundance patterns in HgMn stars (program constrained by time allocation to search for low-excitation lines of Au in stars known to be rich in Pt and Hg) at λ/Δλ ≃ 95000.

Part 5. - Obtain complete UV spectra of selected HgMn stars with high signal-to-noise at λ/Δλ ≃ 25000 for line identification and abundance analyses.

Part 6. - Obtain complete UV spectra of selected normal B and A stars with high signal-to-noise at λ/Δλ ≃ 25000 to establish spectroscopic and abundance comparison standards.

Part 7. - Establish CNO abundances in a characteristic, bright field horizontal branch star using observations of selected low excitation lines at λ/Δλ ≃ 25000.

Part 8. - Obtain complete UV spectra of a bright sharp-lined normal A star and an extremely sharp-lined HgMn star at λ/Δλ ≃ 95000 (lower priority objective to be carried out if time permits).

TABLE 4

HST PROGRAM STARS

Star(HD)	Name	Objective	Star(HD)	Name	Objective
1909	HR 89	1,3	141556	χ Lup	1,3,4,8
17081	π Cet	2	143807	ι CrB	1,3,5
27295	53 Tau	1,3,4,5	145389	φ Her	3,5
33904	μ Lep	1,3	149121	28 Her	3,4
38899	134 Tau	2	174933	112 Her	1,3
48915	α CMa	8	182308	HR 7361	1,3,4
78316	κ Cnc	1,3,5	190229	HR 7664	1,3
89822	HR 4072	1,3,4	193432	ν Cap	1,2,4,6
97633	θ Leo	2	193452	HR 7775	1,3,4,5
110073	HR 4817	1,3	207857	HR 8349	1,3
129174	π^1 Boo	1,3	214994	ο Peg	2,3,6
130095		7	215573	ξ Oct	1,2,3,4,6

I strongly encourage my fellow CP-star aficionados to consider taking advantage of the new opportunities the HST will offer to help us resolve the mysteries of these enigmatic objects.

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