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A Spectroscopic Classification Survey to Search for New ρ Puppis Stars

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Abstract

The ρ Puppis stars are mid-F-type stars that show peculiar chemical-abundance patterns similar to those of the Am stars. Typically they exhibit overabundances of iron-peak elements such as Fe and Ni and *s*- and *r*-process elements such as Sr and Eu, and underabundances of certain other elements including He, Ca, and Sc. It has been proposed that these stars are evolving Am stars passing through the short-lived phase that occurs between the re-establishment of convection and the consequent erasure of their chemical peculiarities. In this paper we suggest a second hypothesis: these stars may have acquired their peculiar abundance patterns in a fashion similar to the Barium stars, i.e., they may have gained the *s*-process element enhancements via mass transfer from a once asymptotic giant-branch companion star, now turned white dwarf. This study will detail our efforts to investigate the ρ Puppis stars with regard to these two hypotheses, with a view to understanding these stars and their significance in terms of stellar evolution. We have performed a spectral classification survey, and a detailed chemical-abundance analysis of selected ρ Puppis stars. This paper gives an overview of the ρ Puppis stars and describes the spectral classification survey which has increased the number of ρ Puppis stars currently known from 6 to 49. A future paper will describe the chemical-abundance analysis which should provide insight into the nature of these stars.

Unified Astronomy Thesaurus concepts: Stellar classification (1589); Chemically peculiar stars (226); Am stars (33); Barium stars (135)

Supporting material: machine-readable tables

1. Introduction

The ρ Puppis classification, established by Gray & Garrison (1989), refers to stars that appear to show abundance patterns similar to those of the metallic-line A-type (Am) stars, but whose effective temperatures resemble those of the mid-F-type stars. Like Am stars, ρ Puppis stars appear to show overabundances of iron-peak elements such as Fe and Ni and of *s*- and *r*-process elements such as Sr and Eu. However, they also tend to show underabundances of certain other elements, including Ca. It has been suggested that the process of diffusion that is held to be responsible for the abundance anomalies in Am stars cannot be maintained below a certain lower effective-temperature limit of F2 [$b - y = 0.22$ mag] (Smith 1973); however, the effective temperatures of ρ Puppis stars are cooler than that limit and yet they still show Am-like abundance patterns.

The most commonly accepted hypothesis to explain the ρ Puppis phenomenon is that these stars are in fact evolving Am stars, caught in the short-lived phase between the re-establishment of convection and the subsequent erasure of the chemical-abundance peculiarities. This hypothesis was initially put forward by Kurtz (1976) to explain the abundance anomalies of the δ Delphini stars. It is suspected that this group may be related to the ρ Puppis stars (see Section 3.1). We suggest here a different hypothesis to explain the abundance anomalies of the ρ Puppis stars, namely, that the ρ Puppis stars are not related to the Am stars, but instead to the Barium stars, a group that shares certain abundance peculiarities with the ρ Puppis stars. The origin of the Ba-star abundance peculiarities is thought to be mass transfer from an asymptotic giant-branch (AGB) companion star, now turned white dwarf (McClure 1983). In this study we report on our investigation of the ρ Puppis stars with respect to these two hypotheses, with a view to determining which (if either) of those physical mechanisms is responsible for producing the observed chemical peculiarities. To that end we first conducted a spectroscopic classification survey which increased the number of ρ Puppis stars currently known from 6 to 49. We then carried out a chemical-abundance analysis of selected ρ Puppis and Am stars that allowed a more detailed look at the chemical makeup of the atmospheres of the target stars. This paper concentrates on the spectroscopic classification survey, following a review of the Am and ρ Puppis stars. The chemical-abundance analysis will be described in a future paper.

2. Background of Am and ρ Puppis Stars

2.1. The Am Stars

The standard explanation of the appearance of Am/Fm abundance anomalies is the model of diffusion/chemical separation (see Watson 1971; Michaud et al. 1983; Charbonneau & Michaud 1991; Charbonneau 1993). In that model, both radiative (g_R) and gravitational (g) accelerations must be considered. Elements for which $g_R > g$ will tend to rise in the atmosphere, whereas those with $g_R < g$ will sink. In normal A- and early F-type stars, rotationally driven meridional circulation overwhelms chemical separation, but below a certain critical rotational velocity, the gravitational settling of helium results in the disappearance of the helium convection zone. In the absence of that zone, chemical separation can occur all the way up to the base of the superficial hydrogen convection zone. This mechanism, when combined with a small mass-loss rate ($\sim 10^{-15}$ $M_\odot$ yr^{-1}), successfully predicts the Am/Fm abundance patterns and the existence and magnitude of the rotational cut-off velocity (Charbonneau 1993). In addition,

Table 1
Stellar Parameters of Known ρ Puppis Stars

ID	$T_{\rm eff}$	log(g)	[Fe/H]	Sp. Type	Reference
ρ Pup	6691	3.23	0.36	kF2hF5mF5 II	Gray et al. (2003)
HD 103877	7200	⋯	0.66	kA7hF5mF5 (II)	The current work
τ UMa	6290	4.10	0.24	kA5hF0mF5 II	Gray et al. (2003) [a]
HD 178875	7300	3.40	0.05	kA9hF2mF3 D	Abt (1984)

Notes. We report median values derived from the bibliographical catalog, PASTEL (Soubiran et al. 2016).
[a] The spectral type determined in the current work is F6 IIIn. See Table 2 for additional notes.

the disappearance of the helium convection zone suggests that Am/Fm stars should not exhibit δ Scuti pulsations (which are driven by instabilities in that zone), and indeed, with very few exceptions, Am/Fm stars are not δ Scuti pulsators (Breger 1970).

It is well known that the incidence of Am/Fm anomalies drops rapidly in the early F-type stars. The chemical separation theory suggests that that behavior is related to the deepening of the superficial hydrogen convection zone with lowering effective temperature, $T_{\rm eff}$. As convective currents deepen, mixing should prevent the gravitational settling of helium. Therefore, radiative diffusion can only lead to the Am-abundance pattern above a certain minimum $T_{\rm eff}$. Furthermore, there exists a critical rotational velocity $V_{\rm crit}$ as a function of $T_{\rm eff}$; a star that is rotating faster than $V_{\rm crit}$ cannot maintain stratification in its atmosphere, so only stars with a rotational velocity of $V_{\rm rot} < V_{\rm crit}(T_{\rm eff})$ will exhibit the Am-abundance pattern (Smith 1973). $V_{\rm crit}$ decreases with $T_{\rm eff}$ until it approaches 0 km s^{-1} at F2, establishing a lower limit for $T_{\rm eff}$ for Am/Fm stars. This finding agrees qualitatively with the discovery that the number of stars with large metallicity (m_1) indices decreases dramatically for types later than F1 [$(b - y) = 0.21$ mag] (Strömgren 1963).

2.2. The ρ Puppis Stars

Gray & Garrison (1989) contested the lower limit determined for $T_{\rm eff}$ for Am/Fm stars, reporting that a small subclass of Fm stars exists that are cooler than spectral type F2. This distinct group had only four members (ρ Pup, θ Gru, HD 103877, and τ UMa) and was labeled ρ Puppis" after the brightest in the class. Since that time, Kurtz et al. (1995) and Murphy et al. (2012) have classified HD 40765 and HD 178875, respectively, as members of the ρ Puppis class to bring the total number of known ρ Puppis stars to six. Stellar parameters and spectral types for four of the six known ρ Puppis stars are reported in Table 1.

From the standpoint of spectral classification, the ρ Puppis stars appear to be quite similar to the Am/Fm stars in that they share the same abundance anomalies, i.e., overabundances of iron-peak and heavy metals (including Sr and Ba), and underabundances of Ca and Sc. Furthermore, ρ Puppis stars exhibit the anomalous luminosity effect, a feature commonly found among Am stars having to do with wavelength-dependent luminosity classification (see Section 3.3 for more detail). The existence of the ρ Puppis stars clearly poses a theoretical problem since they are Am-like stars yet they are cooler than the theoretical lower $T_{\rm eff}$ boundary for the Am-phenomenon (metallicism) established by Smith (1973). However, Gray & Garrison (1989, p. 314) investigated the Balmer jump, via the c_1 index, for each of the known ρ Puppis stars and found that they lie above the zero-age main sequence, suggesting that they "may be unusually cool, *evolved*, Am stars."

Moreover, ρ Puppis itself is known to undergo large-amplitude δ Scuti pulsations (Mathias et al. 1997). It is perplexing on two counts that ρ Puppis exhibits δ Scuti pulsations. The first is that this star presumably lacks the driving mechanism (He ionization) for those pulsations to take place, and yet they are present. The second is that, despite these pulsations, we still see the Am-abundance anomalies that should be erased owing to mixing induced by the pulsations. The fact that ρ Puppis is experiencing δ Scuti pulsations may prove consistent with the theory that ρ Puppis stars are simply evolved Am stars, in that (1) it indicates that either the He ionization zone remained intact or has been re-established in order to drive those pulsations (Kurtz 1976), and (2) it was predicted by Smith (1973) that Am stars that had cooled enough to regain their He ionization zones and that had crossed the critical rotational velocity barrier would be favored to exhibit δ Scuti-type pulsations. Gray & Corbally (2009) corroborated the suggestion of Gray & Garrison (1989), in light of the points above, that ρ Puppis stars may in fact be Am stars in a short-lived phase between the re-establishment of their convective zones and the consequent erasure of their chemical peculiarities, which is in accord with the finding of Kurtz (1976) that evolved Am stars can pulsate while maintaining metallic-line anomalies.

2.3. The Barium Dwarf Stars

We now put forward a second hypothesis to explain the existence of ρ Puppis stars, and suggest that the ρ Puppis stars are related to another group of chemically peculiar F-type stars known as the barium dwarf (Ba dwarf) stars. Barium stars, both giants and dwarfs, show chemical peculiarities somewhat similar to Am stars. It is believed that the barium stars gained those peculiarities via mass transfer from an evolving former AGB companion star, now turned white dwarf (McClure 1983; North & Lanz 1991). Spectroscopically, the Ba dwarfs differ from the Am stars in that all known Ba dwarfs tend only to show enhancements of the *s*-process elements as opposed to an overall metal enhancement as do the Am stars. Furthermore, they have spectral types F4 and later. Nonetheless, there are theoretical reasons to suspect that Ba dwarfs exist with earlier spectral types and higher masses.

Observational evidence suggests that the Ba dwarfs and the Ba giants are linked through their evolution. (1) The Ba giants and the CH subgiants, the latter identified by North et al. (2000), exhibit similar chemical-abundance patterns (Smith et al. 1993). (2) The Ba dwarfs and Ba giants share similar orbital characteristics (North et al. 2000; Escorza et al. 2019). (3) White dwarf cooling times indicate that most Ba giants underwent mass-transfer contamination while still on the main sequence (Böhm-Vitense et al. 2000). Those points imply that the Ba dwarfs are the progenitors of the Ba giants (Böhm-Vitense et al. 2000; North et al. 2000; Gray et al. 2011). Given the masses of the known Ba giants, this hypothesis requires that there should be a significant population of Ba dwarfs with spectral types as early as A0; however, to date no Ba dwarf has been detected with a spectral type earlier than F3. In fact, the Ba giants are statistically more massive than the Ba dwarfs, indicating that only the most massive of the *known* Ba dwarfs will become Ba giants (North et al. 2000; Escorza et al. 2017, 2019). Therefore, it seems that we are failing to detect the massive Ba dwarfs necessary to account for the known Ba giant population. It has been proposed that these missing massive Ba dwarfs may be masquerading as Am/Fm or Ap stars (North et al. 2000; Gray et al. 2011; Escorza et al. 2019). We now propose that it is possible, given their similar abundance patterns, spectral types, and masses, that some of the massive Ba dwarfs may be hiding among the ρ Puppis stars. In fact, the ρ Puppis stars may comprise a subset of Ba dwarfs that are metal-rich. de Castro et al. (2016) and Escorza et al. (2017) report that the Ba dwarfs, on average, have subsolar metallicities, yet the ages of the Ba stars reported by de Castro et al. (2016; 60 Myr–10 Gyr) indicate that most of these objects are younger that the Sun; there is no reason to *expect* Ba dwarfs to be metal-poor. The ρ Puppis stars, which tend to be metal-rich (see Section 3.1) may be the missing link. Another reason to consider our hypothesis will be discussed in Section 4.

If the Ba dwarfs are, indeed, all members of binary systems with white dwarf companions, and the ρ Puppis stars are, in fact, related to the Ba dwarfs, one would expect that the ρ Puppis stars should be found in single-lined spectroscopic binary (SB1) systems. Escorza et al. (2019) determined that the orbital periods of the white dwarf companions of Ba dwarfs range from 1.2 to 23 yr. There is very little evidence in the literature either for or against such orbital periods for the known ρ Puppis stars:

ρ Puppis (single). Rainer et al. (2016) observed ρ Puppis with the High Accuracy Radial velocity Planet Searcher (HARPS) spectrograph (Mayor et al. 2003) 360 times over a period of slightly more than 4 yr (2008 December–2013 January), and found no evidence for binarity.

θ Gru (multiple). θ Gru is a well-known visual binary and has recently been shown to form a physical triple with HD 218205 (Tokovinin et al. 2015). Horch et al. (2000, 2001, 2006) carried out speckle observations of the θ Gru system, but only reported the separation and position angle of the known visual companion. No radial velocity data that could shed light on a possible SB1 nature for θ Gru appears to exist.

HD 103877 (SB?). Grenier et al. (1999) found that this star exhibits radial velocity variations, but the period of those variations was not reported.

τ UMa (SB1). Simbad lists this star as a spectroscopic binary. Bretz (1961) identified τ UMa as an SB1 and determined orbital parameters, including a period of 1062.4 days (2.9 yr).

HD 40765 (single?). Kurtz et al. (1995) finds that HD 40765 is a δ Scuti pulsator with (1) nonsinusoidal light variability with a period of 4.070 hr, (2) a peak-to-peak *B*-magnitude amplitude of 0.21 mag, (3) a peak-to-peak *V*-magnitude amplitude of 0.15 mag, and (4) surface peak-to-peak radial velocity variations of 14 km s^{-1}. They go on to argue that it is extremely unlikely that a hypothesis of binarity could explain these results given the relationship between the amplitude and incidence of δ Scuti pulsation. No long-term radial velocity data appears to exist for HD 40765.

HD 178875 (SB?). Although Dommanget & Nys (1994) and Catanzaro et al. (2011) proposed that HD 178875 is a double system, Murphy et al. (2012, p. 1421) argues that "there is no evidence...to rule out chance alignment" and uses frequency modulation techniques to indicate that it is, in fact, a single star. Additionally, Lampens et al. (2018, p. 7) found small (< 5 km s^{-1}), long-term (several months) radial velocity variations, but because of spectral line profile variations, concluded that the star is "a pulsator accompanied by long-term RV variability." Furthermore, Murphy et al. (2018) employed phase modulation techniques to come to the conclusion that HD 178875 is a single star.

Because the evidence for the binary nature of the known ρ Puppis stars is either nonexistent or inconclusive, we suggest that a better way to decide between the two hypotheses regarding the origin of the abundance anomalies of the ρ Puppis stars is to conduct a detailed chemical-abundance analysis. Barium dwarfs obtain their chemical abundances via the *s*-process which causes enhancements of Sr, Ba, and other *s*-process elements. The ρ Puppis stars also show enhancements of both Sr and Ba (as will be demonstrated), but in our study we will pay close attention to the abundance of Eu, as it is largely an *r*-process element, and is not normally enhanced in Barium stars. If Eu is found to be consistently overabundant in the ρ Puppis stars, it will help to confirm the evolved Am-star hypothesis, whereas if we find solar abundances of Eu in ρ Puppis stars it will point to the mass-transfer hypothesis.

3. A Spectral Classification Survey

3.1. Selection of ρ Puppis Candidates

To date, only six stars are classified as ρ Puppis types. Therefore, our first task was an attempt to discover more members of the class. To that end we followed two observing strategies. The first involved taking a closer look at the stars previously classified as δ Delphini stars, a now defunct classification that was introduced by Bidelman (1965) and whose history is described by Gray & Corbally (2009). Because all of the ρ Puppis stars identified by Gray & Garrison (1989) were initially classified as δ Del stars, we chose additional ρ Puppis candidates from the stars classified as δ Del in the Michigan HD reclassification project (Houk & Cowley 1973), volumes 4 (Houk & Smith-Moore 1988) and 5 (Houk & Swift 1999), which cover declinations accessible from the Dark Sky Observatory. We have obtained spectra of as many of those as possible, at classification resolution.

That δ Del target list of only $\sim$100 stars proved to be too short, and did not provide us with a sufficient number of candidate stars . Upon classification, only six of the observed δ Del targets proved to be ρ Puppis stars. Therefore, we employed a second strategy in which we selected roughly 800 stars from the Mermilliod photometric catalog (Mermilliod et al. 1997) that used Strömgren photometry. Given that the known ρ Puppis stars stand apart from their normal F-type dwarf counterparts in that they have higher metallicities and Balmer jumps that are indicative of the early F-type giants (Gray & Garrison 1989), we selected additional ρ Puppis

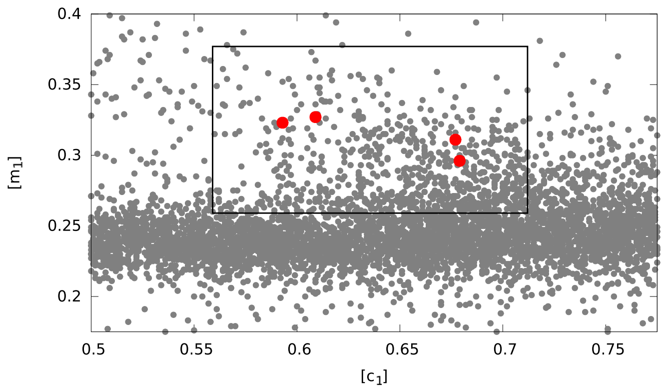

Figure 1. Plot of the Mermilliod Catalog stars according to their *uvby* photometric indices $[m_1]$ and $[c_1]$. Four of the known ρ Puppis stars are indicated by the red dots. The black box indicates the boundaries of the chosen $[m_1]$,$[c_1]$ region from which additional ρ Puppis candidates were selected.

candidates by employing reddening-free versions of the Strömgren metallicity and Balmer jump indices, defined by

$$[m_1] = m_1 + 0.32(b - y) \quad (1)$$

$$[c_1] = c_1 - 0.2(b - y). \quad (2)$$

Figure 1 shows a plot of the stars in the Mermilliod catalog in the $[m_1]$, $[c_1]$ plane. It is evident in that figure that the known ρ Puppis stars are closely grouped, and possess higher $[m_1]$ values than most of the stars with similar $[c_1]$ values. We defined our sample in the $[m_1]$, $[c_1]$ plane by selecting a region (indicated by the box) that contains the known ρ Puppis stars. The additional stars that are contained in that region were then selected as ρ Puppis candidates.

3.2. Classification-resolution Observations

Classification-resolution spectra of 631 of the ρ Puppis candidates were obtained with the Gray–Miller Cassegrain spectrograph on the 0.8 m DFM Engineering telescope of Appalachian State University's Dark Sky Observatory (DSO), located in the Blue Ridge mountains of North Carolina. During the course of our observations, the detector was replaced once. The two detectors that were employed for observations were: (1) a back-illuminated 1024 × 1024 Tektronix CCD (used in the MPP mode) with 24 μm pixels and (2) a 1024 × 256 e2v thinned and back-illuminated thermoelectrically cooled CCD with 27 μm pixels. The 600 and 1200 grooves/millimeter gratings were used in conjunction with a 100 μm wide slit to produce 3.6 and 1.8 Å/2 pixel resolutions ($R = 1300$ and 2300) with spectral ranges of $\lambda\lambda$3800–5600 and 3800–4600 Å respectively. Exposure times were calculated so as to achieve a signal-to-noise ratio (S/N) > 100. The observed spectra were reduced using standard methods (including flat-fielding, dark subtraction, and bias removal) in IRAF.[4] The wavelength calibration was determined using comparison spectra obtained with an Fe–Ar hollow-cathode lamp. The reduced spectra were rectified using an X-Window System program, xmk25, written by R. Gray (Gray & Corbally 2009).

[4] IRAF is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

3.3. MK Spectral Classifications

The spectral classifications of the program stars observed at DSO were carried out on the MK system (Morgan et al. 1943). The current state of this system is described in Gray & Corbally (2009).

In order to understand how the spectra of the ρ Puppis stars compare with those of the Am stars, we first detail the spectral characteristics of Am stars. The spectrum of an Am star is set apart from the spectrum of a normal A-type star in that its metallic-line type appears to be cooler (later) than the hydrogen-line type, and the Ca II K-line type appears to be earlier than the hydrogen-line type. These discrepancies are illustrated in Figure 2. An A- or early F-type star is considered to be Am or Fm, respectively, if the difference between the Ca II K-line type and the metallic-line type is at least five subclasses. Because of these discrepancies between classification features, the Am, Fm, and ρ Puppis stars are classified for each feature separately. The hydrogen-line type of an Am/Fm star is most closely correlated with its effective temperature.

In addition to the hydrogen-line, metallic-line, and Ca II K-line discrepancies, many Am stars exhibit a discrepancy in their luminosity classification criteria too, as mentioned in Section 2.2. In Am stars exhibiting the anomalous luminosity effect (Abt & Morgan 1976), the strength of the luminosity-sensitive Fe II/Ti II blends in the $\lambda\lambda$4395–4480 region will often be comparable to the strength in a normal dwarf star, while—simultaneously—the strength of the Fe II/Ti II blends in the $\lambda\lambda$4172–4179 region and the Sr II lines at λ4077 and λ4216 can be comparable to the strength seen in a giant star, and in some extreme cases even a supergiant. In the case of a star exhibiting the anomalous luminosity effect, it is common practice to determine the luminosity class on the basis on the Fe II/Ti II blends in the λ4172–4179 region, but to emphasize that this class may not reflect the true luminosity of the star, that luminosity class so derived is enclosed in parentheses. Figure 2 illustrates the anomalous luminosity effect in the classical Am star 63 Tau.

Figure 3 illustrates how the ρ Puppis stars resemble the Am stars spectroscopically. Notice that the Ca II K lines of both ρ Puppis stars are weak for their hydrogen-line types. Unlike what is observed in Am stars, the metallic-line types of the ρ Puppis stars tend to be the same as their hydrogen-line types. However, both are "late" as the hydrogen-line type necessary for a ρ Puppis classification is F3 or later (typically F5). Also note that the appearance of the anomalous luminosity effect can be extreme in ρ Puppis stars. In particular, HD 103877 shows line strengths in the $\lambda\lambda$4395–4480 region that are clearly depressed relative to those in the giant standard, 60 UMa, while the Fe II/Ti II blends in the $\lambda\lambda$4172–4179 region are noticeably stronger than those in the giant standard.

Because ρ Puppis stars appear to have similarities to Am stars, we identified stars as ρ Puppis only if they (1) showed Am-type discrepancies in their hydrogen-line, Ca II K-line, and metallic-line types, (2) exhibited the anomalous luminosity effect, and (3) had hydrogen-line types of F3 or later. Our spectral classifications and the broader, corresponding classification families for the ρ Puppis candidates observed at the DSO are presented in Table 2 for stars selected from the the Mermilliod Catalog (Mermilliod sample), and in Table 3 for stars selected from the Michigan HD reclassification project catalogs (Houk sample). Note that in Tables 2 and 3

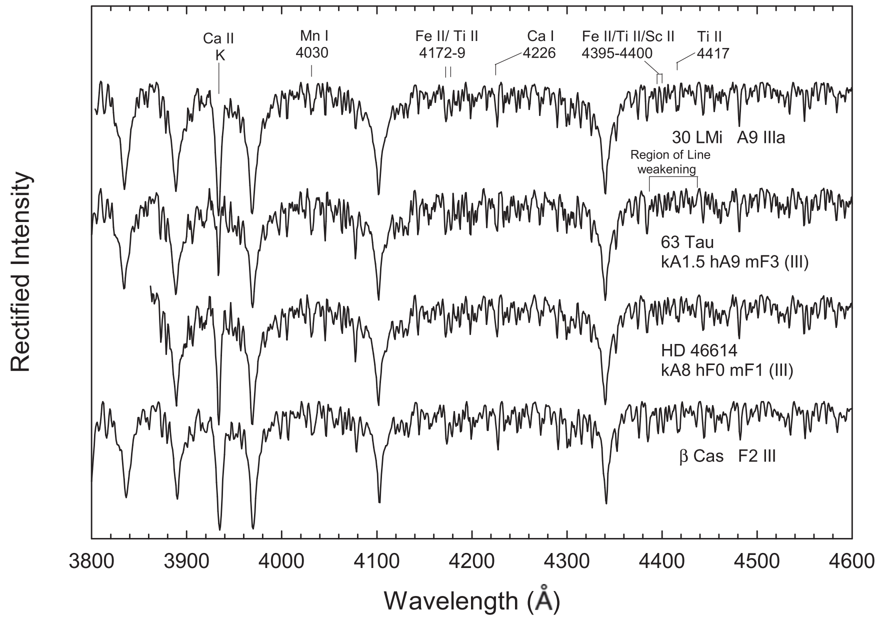

Figure 2. Two Am stars, 63 Tau and HD 46614, are compared with two MK standards, 30 LMi and β Cas. Note that the Ca II K-line of the classic Am star 63 Tau is closer to that of an A1.5 standard star, indicating an earlier temperature type than is indicated by the hydrogen lines, which are a good match with the A9 standard star 30 LMi. In addition, we see that the overall metallic-line spectrum for 63 Tau is somewhat stronger than the F2 standard. The metallic-line type is actually a good match with an F3 standard, and is later than the temperature type indicated by the hydrogen lines. The anomalous luminosity effect can be observed by noting that the Fe II/Ti II blends in the $\lambda\lambda$4395–4480 region in 63 Tau are weaker than those in the same region in the giant standard stars; however, the Fe II/Ti II lines at $\lambda\lambda$4172–4179 are about same strength as those in the standard stars. The standard practice is to use the strength of the features in the $\lambda\lambda$4172–4179 region; it results in a luminosity classification of giant for the Am star. Adapted from a figure from Gray & Corbally (2009), with permission from Princeton University Press.

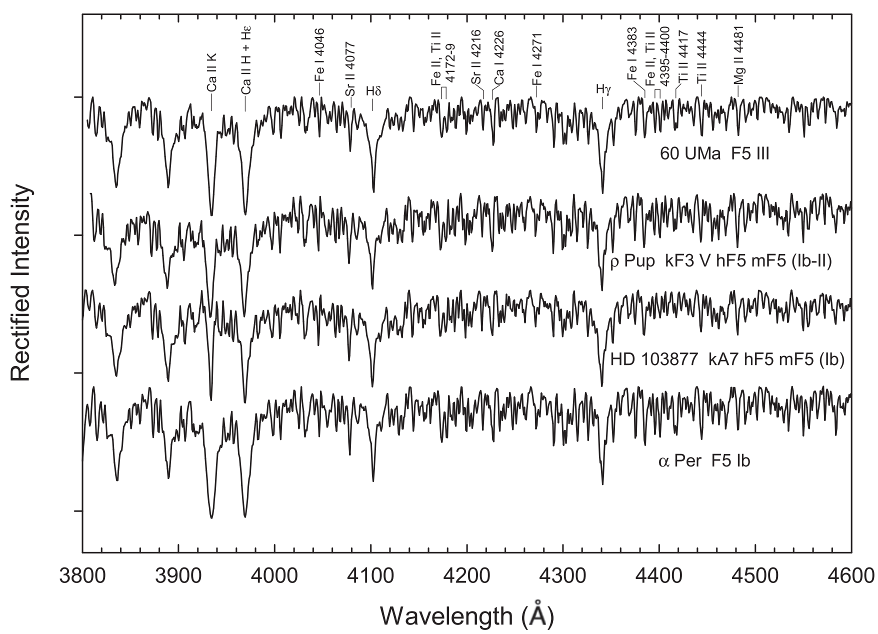

Figure 3. Two ρ Puppis stars, ρ Puppis itself and HD 103877, are compared with two MK standards, 60 UMa and α Per. Note that the luminosity classification for HD 1038777, as shown here, is based on the strong Sr II line at λ4077 and that the luminosity classification for this star depends on the wavelength region used. Adapted from a figure in Gray & Corbally (2009), with permission from Princeton University Press.

the Am/Fm classification families have been further divided using the term "extreme" to denote Ca II K- and metallic-line discrepancies larger than six spectral subclasses, the term "late" to denote metallic-line types of F3 or cooler, and the term "hyper" to denote Am/Fm stars with hydrogen-line types earlier than F3 but that are both "extreme" and "late."

4. Discussion

Of the 631 ρ Puppis candidates, 24% were identified as normal A- and F-type stars and 52% were identified as either Am, Fm, Ba Dwarf, or ρ Puppis (see Table 4). Of the 45 candidates that were classified as ρ Puppis, 43 are new classifications. That significantly increases the number of known ρ Puppis stars.

Table 2
Spectral Classifications and Notes for Stars Selected from the Mermilliod Catalog (Mermilliod et al. 1997)

HD	BD	Mag	Classification Family	Spectral Classification	Notes
16	35.05164	8.092	Normal	F5.5 III-IV	*G* band is sl weak
154	33.04835	8.73	Am	kA8hA8mF1 (III)	Strong ALE; Ba just slightly enhanced
156	−18.06426	7.309	BaD	F4 IV Sr	Mild Ba Dwarf; sl metal weak for F4 IV
416	36.00004	8.87	Hyper Am	kA7hA8mF5 (III) Ba	Mg 4481 enhanced
848	67.00006	8.15	Composite	A/F composite	K-line A2; *G* band F5
1151	1.00025	8.43	Am	kA7hA8.5mF2 (III) Ba	Mg 4481 enhanced
1169	7.00023	7.588	Am	kA8hA9.5mF2 (III)	Mg 4481 enhanced but Ba 4554 normal
1601	48.00084	6.473	Normal	F6 II-III	
1607	21.00025	8.680	ρ Pup	kA5hF5mF5 (III)	ρ Pup
1616	9.00030	8.620	λ Boo[a]	F0 Vn kA6mA5	Possible mild λ Boo star; H lines F0 V, but clearly metal weak; sl rotationally broadened

Note.
[a] We point the reader to Murphy & Paunzen (2017) for a detailed description of the λ Boo stars.

(This table is available in its entirety in machine-readable form.)

Table 3
Spectral Classifications and Notes for Stars Selected from the Michigan HD Reclassification Project (Houk; Houk & Cowley 1973)

HD	BD	Mag	Classification Family	Spectral Classification	Notes
728			Normal	K0 IV	Simbad lists as a variable δ Sct star; further investigation needed
3024			Am	kA7hA9mF1 (III) EuSr	
4630			Am	kA7hA9mF1 (III) SiEuBa	Sr 4077 enhanced but not Sr 4216; Mg 4481 enhanced
7119			Am	kA5hA8mF1 (III) SiEuBa	Sr 4077 enhanced but not Sr 4216
7133			ρ Pup	KA6hF3mF5 (III) SiEuSrBa	ρ Pup
8251			Late Fm	kA8hF0mF4 (III) EuSr	
15306			BaD	F4 kF1mF2 V Sr	Well-known Ba Dwarf
16641			Am	kA5hA7mF0 (III) Ba	
16932			Am	kA4hA9mF0 (III) SrBa	
18460		8.44	Hyper Am	kA7hA7mF4 II	Marginal ALE; H lines better match with lum class III

(This table is available in its entirety in machine-readable form.)

Table 4
Constituents of Classified Stars

Classification Family	Number of Stars	Percentage of Classified Stars
Normal	154	24.3
Am	140	22.2
Fm	136	21.6
ρ Puppis	44	7.1
Ba Dwarf	6	1.0
λ Boo	2	0.3
SB2[a]	2	0.3
Composite[b]	54	8.6
Peculiar[c]	42	6.8
Rapid Rotator[d]	51	7.9
Total	631	…

Notes. The broad classification "family" categories encountered in this work are listed here. The percentage of stars that fell into each group are calculated with respect to the entire candidate list including both the Mermilliod and the Houk samples.
[a] The spectra of these stars show double-lined features at classification resolution ($R = 2300$).
[b] The Ca II K-line region of a composite spectrum tends to be dominated by the early star, whereas the *G*-band region tends to be dominated by the late star.
[c] The specific peculiarities of the individual spectra are indicated in the notes section of the classification tables (Tables 2 and 3).
[d] These spectra are marked by significant broadening of the spectral features.

Interestingly, among the Am, Fm, and ρ Puppis stars in our sample there is a bimodal distribution according to hydrogen-line type, which is the dominant factor in determining whether or not a ρ Puppis-like star is considered to be a bona fide ρ Puppis member (see Figure 4). A peak in the number of stars at the hydrogen-line type A9 is evident, and after that the number of stars drops off sharply. The sharp disjunct peak at F5 corresponds to the ρ Puppis stars. The rapid drop in the number of Fm stars after F1 is in accord with the results of Smith (1973) and Michaud et al. (2005), but the existence of the ρ Puppis stars as a well-separated group is new. The Hartigan dip test of unimodality (Hartigan & Hartigan 1985) was performed for both the Mermilliod and the Houk frequency distributions of Am, Fm, and ρ Puppis stars by hydrogen-line type; it yielded dip statistics of 0.11379 and 0.09375 for sample sizes of $N = 272$ and $N = 48$ for the Mermilliod and the Houk samples, respectively. The corresponding probability that the distribution is at least bimodal is over 99.9% for the Mermilliod sample and between 99.5% and 99.9% for the Houk sample, indicating that the ρ Puppis stars do indeed form a second population whose origin *may* be physically distinct from that of the Am/Fm stars. That result motivates us more strongly to explore the mass-transfer (Ba dwarf) hypothesis put forward in Section 2.2 by carrying out a chemical-abundance analysis to be described in a future paper.

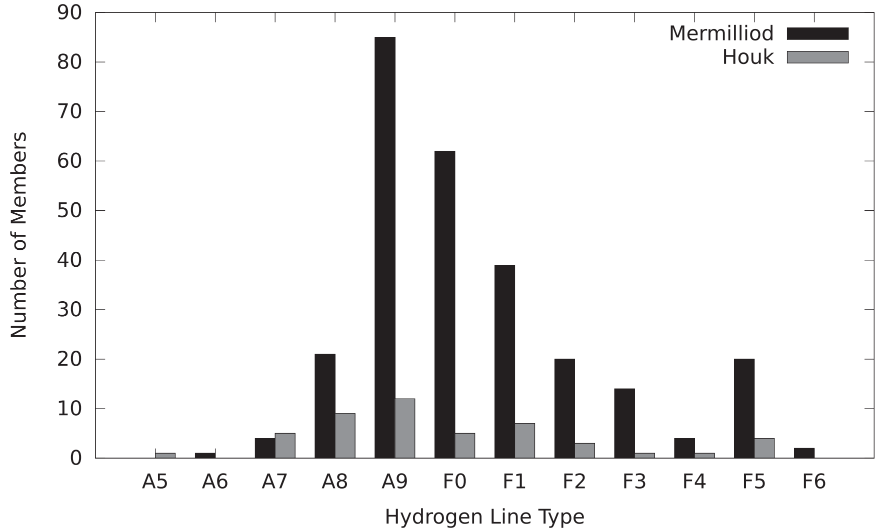

Figure 4. Am, Fm, and ρ Puppis stars grouped according to the hydrogen-line (H-line) type.

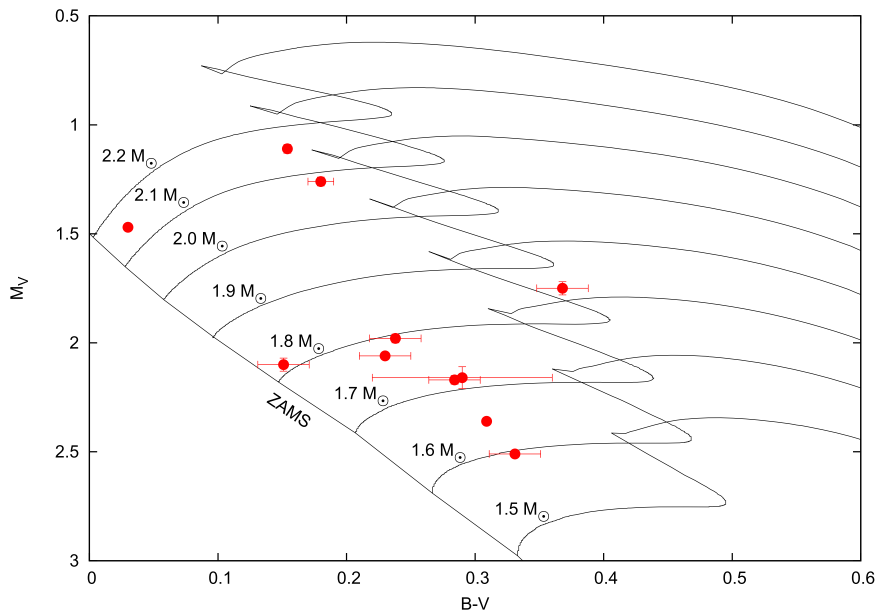

Figure 5. 11 Am stars identified in the NStars project are compared to the solar–metallicity evolutionary tracks of Pietrinferni et al. (2004) for stars between $1.5M_{\odot}$ and $2.2M_{\odot}$. Uncertainties in M_V and $B - V$ are shown for the eight stars that have published B and V errors. It can be seen that only two of these stars appear to be true zero-age main-sequence stars, six appear to be evolved main-sequence stars, and three appear to be nearing the termination of core hydrogen fusion.

Abt (2017) argues against the hypothesis that ρ Puppis stars are Am-star descendants by pointing out that in the Bright Star Catalog (BSC; Hoffleit & Jaschek 1982), the number of ρ Puppis stars relative to the number of Am stars is too small by a factor of roughly 100. This is determined by considering the main-sequence and subgiant evolutionary lifetimes which are nearly equal, and are intended to correspond to the Am stars and ρ Puppis stars respectively. It should be noted, however, that the BSC is neither a volume-limited sample, nor have many of its classifications been confirmed (Griffin et al. 2012), so this estimate may not be accurate. A second issue with this argument becomes clear when we consider the Am stars in the volume-limited NStars sample (Gray et al. 2003, 2006). Figure 5 plots 11 of the 13 Am stars that were identified in the NStars project and for which Gaia parallaxes exist (Gaia Collaboration et al. 2016, 2018). Evolutionary tracks from Pietrinferni et al. (2004) for solar–metallicity stars between $1.5M_{\odot}$ and $2.2M_{\odot}$ are also plotted. It is evident that 9 of the 11 Am stars are in fact evolved in the sense that they no longer lie near the zero age main sequence (ZAMS); indeed 3 of them are near the hydrogen-exhaustion stage. It may be that many of the Am stars identified in the BSC are also evolved, should therefore be included with the ρ Puppis stars when determining the ratio of normal Am stars to evolved Am-type stars, and would thereby reduce the aforementioned factor of 100. Additionally, when we consider a timescale for the short-lived evolutionary state in the evolved Am-star hypothesis, we must remember that ρ Puppis stars lie in a temperature range where convection in the outer envelope is important and that it is the convective mixing rather than the subgiant evolutionary timescale that is relevant; it is convection that will erase the ρ Puppis chemical peculiarities from the atmosphere (see Section 2.1). Since the convective timescale is much shorter than the evolutionary timescale, this also helps to explain why the number of ρ Puppis stars is smaller than the number predicted by Abt. As a case in point, the composite-spectrum binary system, o Leo, supports the plausibility of a short-lived phase of evolution between the re-establishment of convection and the erasure of the chemical peculiarities for Am stars. The primary component of o Leo may be an example of an extremely late ρ Puppis star given its Am-like abundance anomalies, cool temperature($T_{\rm eff} = 6100$ K), and therefore late spectral type (∼F8). Griffin (2002) examines various scenarios and concludes that it is likely that o LeoA is experiencing the short-lived phase of evolution described in the present work. Furthermore, Griffin (2002) argues that the rarity of binaries similar to o LeoA suggests that this phase is extremely rapid.

The next step in this investigation is to conduct a detailed chemical-abundance analysis of the ρ Puppis stars in order to gain more insight into the chemical makeup of the atmospheres of these stars. We hope it will help to answer the question of whether these stars are in fact related to the Am stars or to the Ba dwarfs.

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