DISCOVERY OF TWO RARE RIGIDLY ROTATING MAGNETOSPHERE STARS IN THE APOGEE SURVEY

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ABSTRACT

The Apache Point Observatory Galactic Evolution Experiment (APOGEE)—one of the Sloan Digital Sky Survey III programs—is using near-infrared (NIR) spectra of ∼100,000 red giant branch star candidates to study the structure of the Milky Way. In the course of the survey, APOGEE also acquires spectra of hot field stars to serve as telluric calibrators for the primary science targets. We report the serendipitous discovery of two rare, fast-rotating B-stars of the σ Ori E type among those blue field stars observed during the first year of APOGEE operations. Both of the discovered stars display the spectroscopic signatures of rigidly rotating magnetospheres (RRM) common to this class of highly magnetized ($B \sim 10$ kGauss) stars, increasing the number of known RRM stars by ∼10%. One (HD 345439) is a main-sequence B-star with unusually strong He absorption (similar to σ Ori E), while the other (HD 23478) fits a "He-normal" B3IV classification. We combine the APOGEE discovery spectra with other optical and NIR spectra of these two stars, and of σ Ori E itself, to show how NIR spectroscopy can be a uniquely powerful tool for discovering more of these rare objects, which may show little/no RRM signatures in their optical spectra. We discuss the potential for further discovery of σ Ori E type stars, as well as the implications of our discoveries for the population of these objects and insights into their origin and evolution.

Key words: stars: chemically peculiar – stars: early-type – stars: individual (HD 23478, HD 345439) – stars: magnetic field

Online-only material: color figures

1. INTRODUCTION

σ Orionis E is the archetype of an unusual and rare class of helium-strong main-sequence B-stars (Gray & Corbally 2009), characterized by extremely large magnetic fields and fast rotation. σ Ori E itself has a measured longitudinal magnetic field varying with an amplitude of $B_l \sim 2$–3 kG with an inferred polar magnetic strength of ∼10 kG (Townsend et al. 2005; Kochukhov et al. 2011; Oksala et al. 2012) a rotational velocity of $v \sin i = 160$ km s^{-1}, and a rotational period of 1.19 days (Townsend et al. 2005). The high magnetic field of the star is thought to form a rigidly rotating magnetosphere (RRM; Townsend et al. 2005, 2010) which traps circumstellar material in two co-rotating clouds at a distance of several stellar radii beyond the photospheric surface, producing an extremely broad, double-horned Hα emission profile with velocity width >1000 km s^{-1} as well as periodic modulation of the star's light curve. The magnetic field also appears to be responsible for the enhanced He absorption via localized surface abundance anomalies it creates in the star. A more recently discovered star in the same class, HR 7355 (Rivinius et al. 2008, 2010; Oksala

et al. 2010), shows similarly He-strong absorption and polar field strength ($B \sim 11$–12 kG) to σ Ori E, and corresponding Hα emission profiles with velocity widths of ∼1300 km s^{-1}. HR 7355 shows exceptionally fast rotation ($P = 0.52$ days and $v \sin i = 310$ km s^{-1}); this star, along with HR 5907 ($P = 0.51$ days, $v \sin i = 340$ km s^{-1}), are the two fastest-rotating, non-degenerate magnetic stars known—in fact, their speeds approach the rotational breakup velocity (Rivinius et al. 2013; Grunhut et al. 2012). The simultaneous presence of such extreme rotation and large magnetic field is somewhat surprising for massive B-stars, and for HR 7355 the spindown timescale via magnetic braking should be much shorter than its estimated age (Rivinius et al. 2013; Mikulášek et al. 2010). Thus, these stars provide a unique conundrum for theories of both star formation and magnetic field evolution. Increasing the known number of these objects will allow us to understand how common this phenomenon is for massive stars, and establish the range of properties they can exhibit.

In this paper, we present the discovery of two additional members of this rare class of stars from the Sloan Digital Sky Survey III's Apache Point Observatory Galactic Evolution
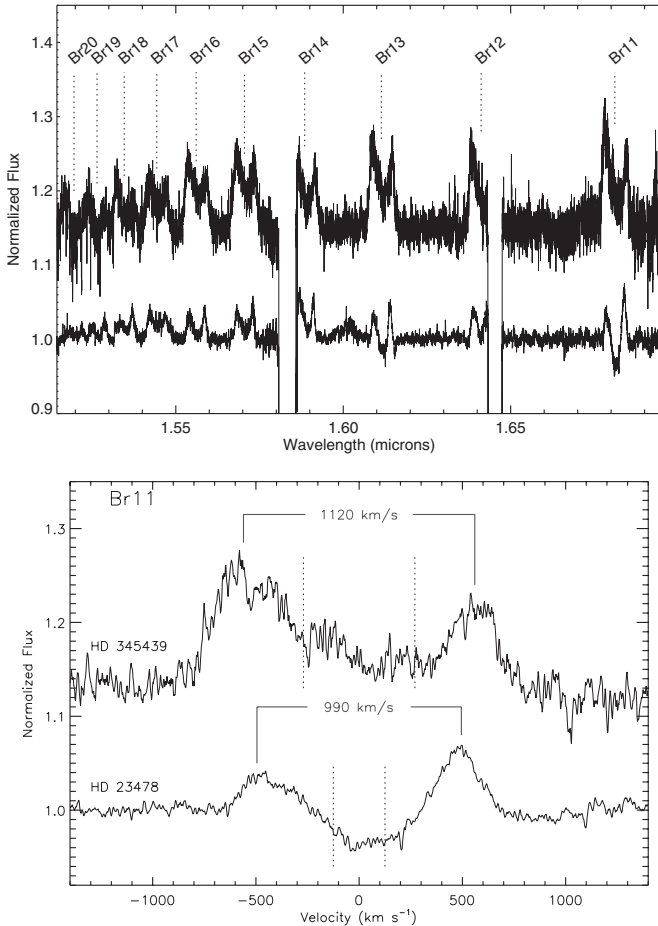
Figure 1. Top: APOGEE discovery spectra of the emission-line character of the stars HD 345439 (upper) and HD 23478 (lower). The pronounced double-horned Brackett series emission lines dominate the *H*-band spectrum of these stars. The gaps near $1.583\,\mu$m and $1.647\,\mu$m are due to the inter-detector spacing in the APOGEE detector focal plane. (Bottom) Expanded view of the Br11 ($1.681\,\mu$m) profiles for HD 345439 (top) and HD 23478 (bottom). The double-horned velocity profile with peak separations of $\sim$1000 km s^{-1}, significantly exceeding the range of $\pm v \sin i$ (indicated by the dotted vertical lines), is characteristic of the rigidly rotating magnetosphere (RRM) stars of the σ Ori E class. The spectra have been rebinned by a factor of four from the native APOGEE resolution for an improved signal-to-noise ratio for these broad features. The spectrum of HD 345439 has been offset by 0.1 in intensity for clarity.

Experiment (SDSS-III/APOGEE; Gunn et al. 2006; Eisenstein et al. 2011; Wilson et al. 2012; S. Majewski et al. in preparation). APOGEE is a near-infrared (NIR), *H*-band (1.51–$1.70\,\mu$m), high-resolution ($R \simeq 22{,}500$), spectroscopic survey primarily targeting red giant stars in the Milky Way. As part of routine survey operation, APOGEE selects bright, hot, blue stars in each survey field for telluric correction of the red giant spectra. Below, we describe the serendipitous discovery of the two σ Ori E type stars among these APOGEE telluric standards, identified via the unique magnetospheric signatures they produce in their Brackett series emission profiles. We next present optical spectra that confirm the He-strong classification of one star and the apparent "He-normal" nature of the other, allow measurements of $v \sin i$, and show evidence of Hα profiles matching the Brackett series RRM signatures. We also present Triplespec NIR spectra of these two stars and σ Ori E itself, which confirm the similarities among all three stars and the "smoking gun" signature provided by the Brackett series line profiles created by the RRMs in these stars. We conclude by
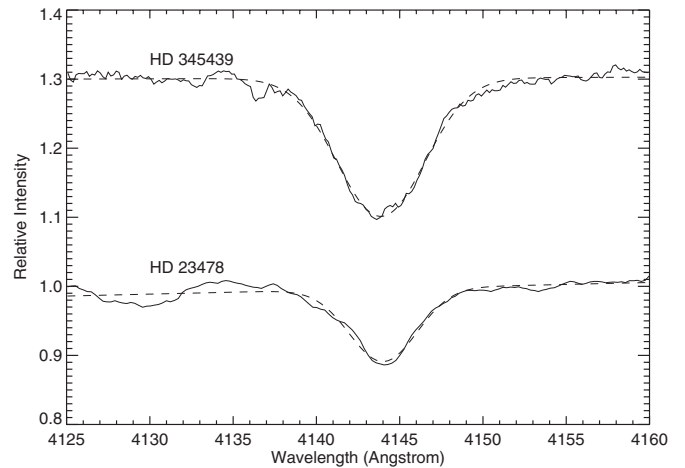
Figure 2. Line profile fits to He I absorption lines used to determine $v \sin i$. We used simple Gaussian absorption profiles, which seem to provide accurate fits for both stars' broad absorption lines. We use multiple lines for each star; the plot above shows He I λ4144.

discussing the potential for further discovery of σ Ori E type stars during the APOGEE survey, and the implications they will have for understanding the breadth of characteristics in the population of these objects, their origin, and their evolution.

2. OBSERVATIONS AND SPECTRAL ANALYSES

2.1. APOGEE Near-IR Discovery Spectra

To assess and remove telluric absorption features from APOGEE science spectra, 35 of the 300 instrument fibers used in each observation are used to observe hot, blue stars simultaneously with the normal science targets (Zasowski et al. 2013). The first 18 telluric calibrators selected are subject to a spatial constraint, whereby the APOGEE field in question is divided into 18 equal-area zones and the bluest star (in raw $J - K_s$ color, with $5 < H < 11$ mag) in each zone is selected as a target. The remaining 17 telluric calibrators are simply the bluest stars anywhere in the field of view not previously selected. Visual inspection of these spectra led to the identification of numerous Be stars, which we placed into a numbered list (in order of discovery) for further study. HD 23478 (ABE-075) was observed a total of nine times, with approximately 1 hr observation each time, on the six different fiber plug plates designed for a special study of the young open cluster IC348. HD 345439 (ABE-050), however, was only observed on an APOGEE instrument commissioning fiber plate (a plate designed for testing of sky and telluric removal). While this plate was observed twice, the second observation produced poor signal-to-noise ratio (S/N). Fortunately the first observation achieved good S/N ($\sim$70 per resolution element in the continuum).

In Figure 1, we present the APOGEE NIR discovery spectra for the two newly identified σ Ori E stars—labeled ABE-050 (HD 345439) and ABE-075 (HD 23478) in the APOGEE catalog of Be stars. In the APOGEE bandpass, we can see prominent Brackett series emission lines (Br11-Br20) from both stars, each with a characteristic double-horned profile. In Figure 2, we display a detailed view of the Br11 line profiles from each star—as may be seen, the profile peak separations approach $\sim$1000–1100 km s^{-1}, which is $\sim$2 times greater than the largest linewidths seen from more "normal" Be stars observed by APOGEE (D. Chojnowski et al., in
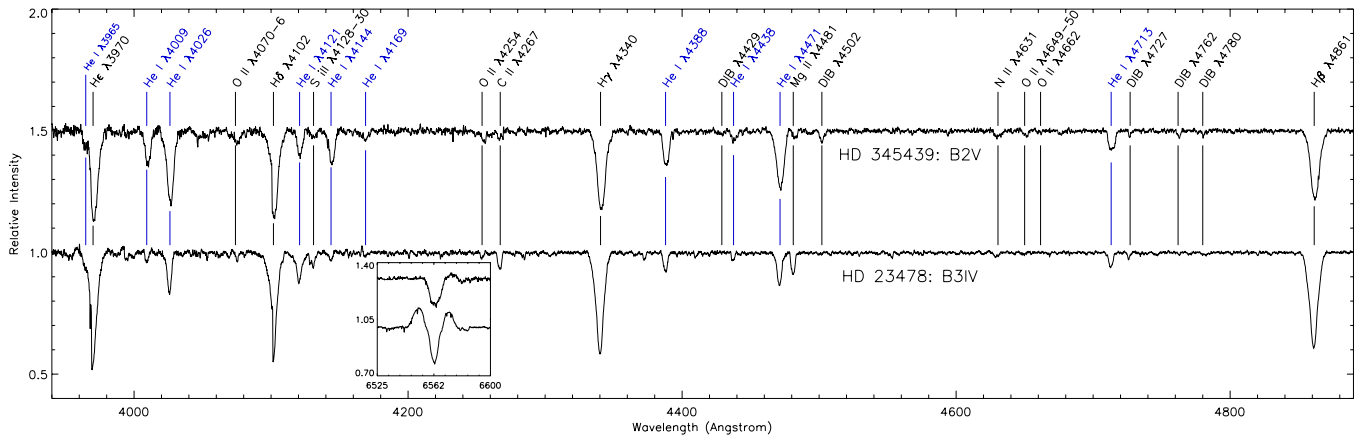
Figure 3. HET optical spectra of HD 345439 and HD 23478, with HD 345439 offset by 0.3 in relative intensity from HD 23478, and including key line identifications for spectral classification (including some diffuse interstellar bands—DIBs). Inset plot shows the region around Hα for both stars. The He I features are generally stronger and broader in HD 345439 than in HD 23478. HD 23478 exhibits the broad Hα RRM signatures at this observation epoch, while HD 345439 shows only a slight emission "bump" on the red side at this epoch. These spectra are not contemporaneous with the NIR spectra from APOGEE nor Triplespec.
(A color version of this figure is available in the online journal.)

preparation). This type of profile and peak separation is typical of the RRM feature of σ Ori E stars, and is strong evidence that HD 345439 and HD 23478 are likely to be rapidly rotating, highly magnetized stars. In short, the APOGEE infrared color selection for telluric standards (which selects stars with colors roughly similar to B-stars) and APOGEE spectra alone make these stars strong candidates for the σ Ori E type classification.

2.2. Optical and Triplespec Near-IR Spectra

Based on this initial identification, we obtained followup optical spectra of HD 345439 and HD 23478, as well as 1–2.5 μm NIR spectra of both stars and σ Ori E itself to confirm the identification. In the optical, we observed both stars using the high-resolution spectrograph (Tull 1998) on the Hobby–Eberly Telescope (HET; Ramsey et al. (1998)) as part of queue-scheduled observing in the lower priority band (Shetrone et al. 2007) at $R = 18000$ with the cross disperser set to achieve spectra from 3910–4880 Å on the blue detector and from 4990–6820 Å on the red detector. We reduced the spectra with IRAF[15] ECHELLE tasks, using the standard IRAF tasks for overscan removal, bias subtraction, flat fielding, scattered light removal and wavelength calibration. We present the resulting spectra in Figure 3.

At first glance, the optical spectra of both stars—especially the region blueward of Hα—resemble those of typical B-stars, with strong Balmer absorption lines as well as prominent He absorption features. However, the absorption lines show very broad symmetric profiles that indicate high rotational velocities, and for HD 345439 the He I lines are unusually strong. Comparing its spectrum to the typical B-stars in Gray & Corbally (2009), the presence and strength of the He I lines constrain HD 345439 to be in the spectral range of O9–B3. The absence of He II 4686 Å constrains both stars to be later than B0, and HD 345439 closely matches B1V or B2V stars in the strength of Si II λλ4128–4130 and Mg II λ4481, which are key indicators in this sequence (Walborn & Fitzpatrick 1990). Furthermore, the strength of He I 4026 Å, O II 4070–4076 Å, and the lack of detectable emission from O II 4348 Å, O II 4416 Å,

and Si III 4553 Å all confirm the main-sequence classification of this star. However, none of the "normal" stars in Gray & Corbally (2009) possess the He I absorption strength we see in HD 345439. HD 23478, on the other hand, appears optically to be a fairly "normal" star at first glance, based on the blue part of its spectrum, with much weaker He absorption than HD 345439. This object was previously classified as a B3IV star (Hiltner 1956; Crawford 1958; Walker 1963), and this classification is confirmed in our spectrum by the presence and strength of the Mg II 4481 Å, C II 4267 Å, and Si II 4128–4130 Å absorption features. However, the He I ratio of 4144 Å/4121 Å is ≪1.0 in HD 23478—a peculiarity not seen in other stars, where the ratio is typically ≳1.0 (Walborn & Fitzpatrick 1990; Gray & Corbally 2009). Furthermore, the Hα features in both HD 345439 and HD 23478 display the pronounced broad emission typical of RRM stars in both HD 23478 and HD 345439.

We also obtained Triplespec (Wilson et al. 2004) NIR spectra of HD 345439, HD 23478, and σ Ori E itself (Figure 4), using the APO 3.5 m. We used the 1″.1 slit, for $R \sim 3500$ spectra between 0.95–2.46 μm, and all data were acquired nodding in ABBA mode. Eight 90 s integrations of HD 345439 and twenty 20 s integrations of the A0V star HD 189690, used for telluric correction (Vacca et al. 2003), were obtained on 2012 September 3. Eight 30 s integrations of HD 23478 and four 30 s integrations of the A0V star HR 1724 were performed on 2013 February 15. Six 60 s integrations of σ Ori E and six 60 s integrations of the A0V star HD 67015 were obtained on 2013 January 25. These data were reduced using Triplespectool, a modified version of Spextool developed for use with the SpeX instrument at IRTF (Cushing et al. 2004). The strongest features of all three spectra are again the extremely broad double-horned Brackett-series emission profiles that distinguish the RRMs of these stars. HD 345439 appears to have the strongest RRM feature at these particular epochs of observation, while HD 23478 and σ Ori E are similar in emission strengths/widths (with σ Ori E being slightly more asymmetric and with deeper absorption depth at these epochs). Here again HD 23478 shows significantly weaker He I absorption features (i.e., at 1.70 μm and at 2.11 μm) than the other two stars. The persistence of this weak absorption at multiple epochs seems to indicate that HD 23478 may truly be more "He-normal" than HD 345439 and the RRM archetype σ Ori E—though more data are needed to confirm this conclusion.

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[15] IRAF (Image Reduction and Analysis Facility) is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under contract with the National Science Foundation.
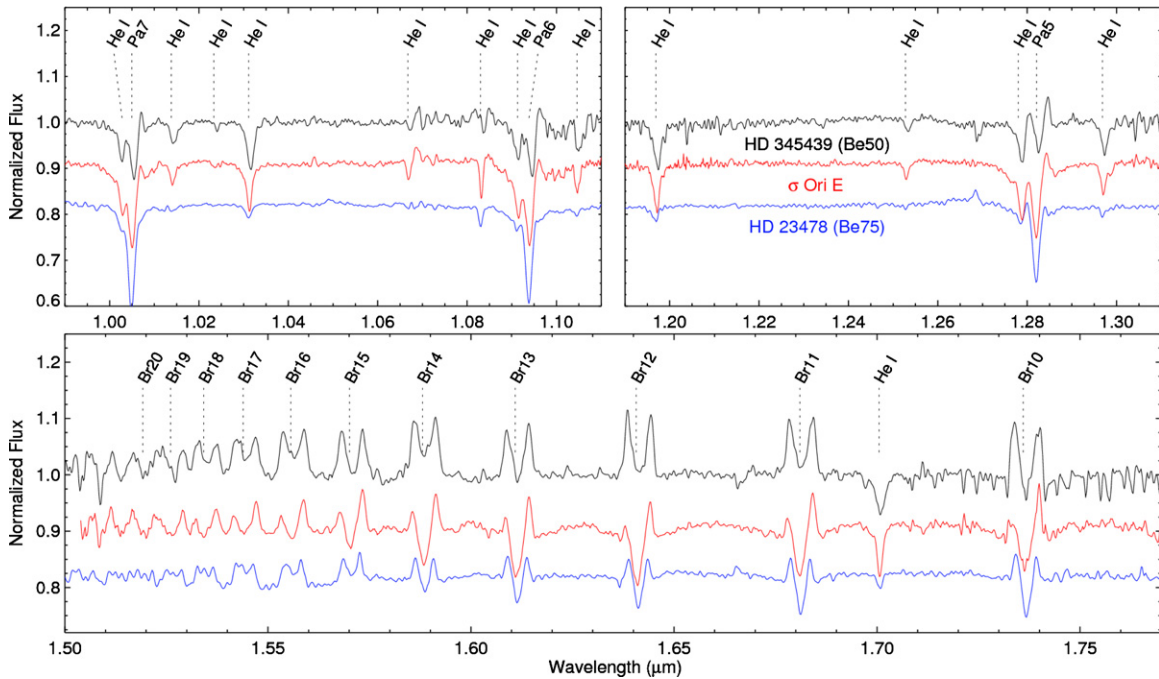
Figure 4. Portions of the normalized Triplespec NIR spectra of HD 345439 (black), HD 23478 (blue), and the RRM star archetype σ Ori E (red). The RRM features are seen in all lines of the Brackett series. Also, HD 23478 is noticeably weaker in its He I absorption features than the other two stars.
(A color version of this figure is available in the online journal.)

To measure $v \sin i$ for the stars, we fit line profiles for the He I absorption features at 4026 Å, 4144 Å, 4388 Å, and 4471 Å and account for non-rotational effects according to the correction factors in Daflon et al. (2007), which then lead to $v \sin i$ values of $270 \pm 20 \, \mathrm{km \, s^{-1}}$ for HD 345439 and $125 \pm 20 \, \mathrm{km \, s^{-1}}$ for HD 23478. These measurements are typical of the fast-rotating highly magnetized σ Ori E stars—the $v \sin i$ for HD 23478 is very similar to (albeit slightly slower than) the value for σ Ori E itself, while HD 345439 appears to be one of the fastest known rotators among main-sequence stars, surpassed only by the two recently discovered σ Ori E stars, HR 7355 and HR 5907. Previous work (Jerzykiewicz 1993) indicates a photometric period for HD 23478 of 1.0499 days, which is also very similar to (and slightly faster than) the measured 1.19 days rotation period of σ Ori E. These rotational properties confirm our classification of HD 345439 and HD 23478 as σ Ori E stars.

We measured the He I equivalent widths for both stars and present them along with values for typical B-stars, as well as σ Ori E, in Figure 5. Again, this confirms that HD 345439 is typically "He-strong," as are other σ Ori E stars, while HD 23478 may be "He-normal," despite being a fast rotator with the clear signature of a RRM. We note that helium absorption strength can be phase-dependent in the σ Ori E stars, and the variations may be large enough to mask their "He-strong" nature at some rotational phases, so additional phase-sampled spectra are required to confirm this conclusion.

3. DISCUSSION

The σ Ori E stars present a mystery for stellar evolution. B-stars should not have large convective zones, and thus are expected to possess relatively weak magnetic fields—but typically measured field strengths for σ Ori E analogs are $\sim$10 kG and higher, in apparent (and strong) contradiction of this theoretical expectation. Furthermore, most theories predict that young B-stars should spin down on a $\sim$1 Myr timescale, but
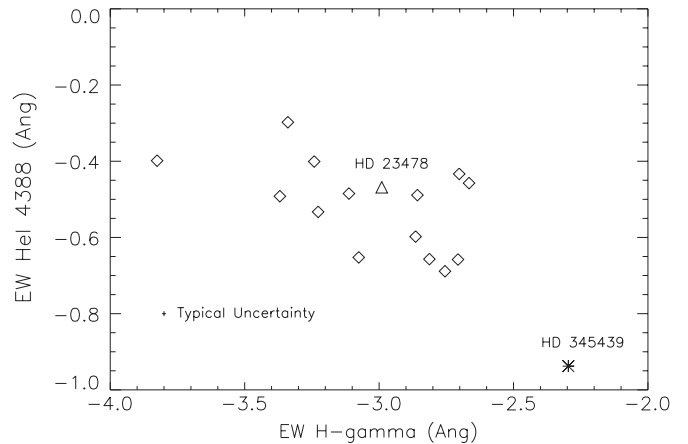
Figure 5. He I and Hγ equivalent widths for the HET standard B-stars (diamonds), as well as HD 345439 (asterisk) and HD 23478 (triangle). HD 345439 clearly is an outlier from the normal B-stars, while HD 23478 appears to be "He-normal" in these observations.

the σ Ori E star HR 7355 appears to be 15–25 Myr old (Rivinius et al. 2013; Mikulášek et al. 2010) and yet has a high rotational velocity. While we cannot measure the magnetic field from our current data, the unique RRM signature clearly indicates that HD 345439 and HD 23478 are also magnetized stars (which future spectropolarimetry observations could confirm), and they are both definitely fast rotators. While the RRM can theoretically arise in any star where the Alfven radius exceeds the Kelperian co-rotation radius (ud-Doula et al. 2006, 2008), in which case fields as low as $\sim$1 kGauss could suffice, the other resemblances between these stars and the σ Ori E stars seem to imply that similar field strengths of $\sim$10 kGauss are most likely. In the case of HD 23478, its sky position, parallax of 4.99 mas, and proper motion of $+8 \, \mathrm{mas \, yr^{-1}}$, $-8 \, \mathrm{mas \, yr^{-1}}$ (Van Leeuwen 2007) all match the members of the IC 348 young open cluster (Scholz

et al. 1999). This result constrains the age of HD 23478 to match that of IC 348—previously estimated as 1.3–3 Myr by Herbig (1998); Bell et al. (2013) however have recently derived an age closer to ∼5–6 Myr based on current isochrone-fitting techniques. Future measurements of the magnetic field in this star can then provide an estimated spindown timescale, to see if this star matches expectations or, like HR 7355, seems to be spinning too fast for its age and magnetic field.

As this work has shown, a particularly promising avenue for identifying more of these unusual stars is NIR spectroscopy. We believe the APOGEE spectra in Figure 1 to be the first published NIR spectra of σ Ori E stars, and they are remarkable in the strength of the RRM signatures in the Brackett lines. Based on our sample of spectra (which are admittedly few in number and sparse in phase sampling), each individual Brackett transition shows stronger RRM signatures than Hα for the same star, and the presence of 10 transitions in just 2/3 of the H-band makes the NIR an exceptionally powerful new diagnostic approach for identifying σ Ori E stars. Our discoveries were entirely serendipitous, yet they have increased the known sample of these stars by ∼10%, and HD 345439 alone has enhanced the number of "extreme" (near-breakup velocity) rotators by 50%. Furthermore, the optical spectra of these stars are much more "normal" than their NIR spectra—both HD 23478 and HD 345439 have previous optical observations and classifications that entirely missed their RRM nature. We can see in Figure 4 that the Brackett series RRM signatures are substantially stronger than even the NIR Paschen series, indicating that the NIR H-band may be a "sweet spot" for this diagnostic. The fact that HD 23478 is both nearby and bright in the optical, yet eluded RRM classification until now, further accentuates the diagnostic power of NIR spectroscopy for this work. Thus, with the advent of powerful IR spectrographs at many observatories, and of large-scale IR spectroscopic surveys such as APOGEE, we can speculate that the discovery of these previously rare stars may accelerate quickly in the near future.

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