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Pleiades or Not? Resolving the Status of the Lithium-rich M Dwarfs HHJ 339 and HHJ 430

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Abstract

Oppenheimer et al. discovered two M5 dwarfs in the Pleiades with nearly primordial lithium. These stars are not low enough in mass to represent the leading edge of the lithium depletion boundary at Pleiades age (∼125 Myr). A possible explanation for the enhanced lithium in these stars is that they are actually not members of the Pleiades but instead are members of a younger moving group seen in projection toward the Pleiades. We have used data from Gaia DR2 to confirm that these two stars, HHJ 339 and HHJ 430, are indeed not members of the Pleiades. Based on their space motions, parallaxes, and positions in a Gaia-based color–magnitude diagram, it is probable that these two stars are about 40 parsecs foreground to the Pleiades and have ages of ∼25 Myr. Kinematically they are best matched to the 32 Ori moving group.

Unified Astronomy Thesaurus concepts: Moving clusters (1076); Star clusters (1567); Open star clusters (1160)

1. Introduction

Star-forming regions and young open clusters provide the laboratory data for how star formation and early stellar evolution proceed. This only works, however, if it is possible to attach ages to each of the laboratory populations. The more accurate the ages, the better the historical reconstruction. It was realized more than 60 years ago[12] that the photospheric lithium abundance in low-mass stars might provide one means to determine those ages. Very young low-mass stars in star-forming regions usually have nearly primordial lithium abundances (Bonsack 1959; Bonsack & Greenstein 1960). There is a clear decrease in the mean lithium abundance as a function of mass as one goes from stars of a few megayears age (e.g., Orion or Taurus star-forming region, hereafter SFR) to stars of order 100 Myr (e.g., Pleiades) to stars of order 600 Myr (e.g., Hyades) age (Soderblom et al. 1993; Sestito et al. 2008; Cummings et al. 2017). While this dependence is clear when comparing data for large ensembles of stars, there is significant dispersion in lithium abundance at a given mass, such that it is not possible to assign accurate ages on a star-by-star basis.

In the early 1990s, it was realized that lithium might become a quite accurate age indicator for objects with masses near 0.1 $M_\odot$ (Bildsten 1997), because below a certain mass the core temperature never becomes hot enough to burn lithium, and these fully convective objects should therefore retain their primordial lithium abundance forever. Measuring the mass below which all stars (and substellar objects) in a young open cluster still retain nearly primordial lithium abundance therefore was predicted to provide a quite accurate age for all the stars in the cluster, assuming that the stars in the cluster are essentially coeval. The first cluster for which an accurate lithium depletion boundary (LDB) age was measured was the Pleiades (age 125 Myr; Stauffer et al. 1998). Subsequently, LDB ages have been derived for the open clusters Alpha Persei, Blanco 1, NGC 1960, NGC 2516, NGC 2547, IC 2391, IC 4665, and Hyades (Jeffries et al. 1998; Stauffer et al. 1999; Barrado et al. 2004; Jeffries & Oliveira 2005; Manzi et al. 2008; Cargile et al. 2010; Jeffries et al. 2013; Martin et al. 2018) and for the Beta Pic and Tuc-Hor moving groups (Binks & Jeffries 2014; Kraus et al. 2014).

In one of the earliest attempts to determine the LDB in an open cluster, Oppenheimer et al. (1997) obtained spectra of a sample of the faintest Pleiades members drawn from the Hambly et al. (1993; HHJ) proper-motion survey. They were unsuccessful in their quest because the faint limit of the HHJ survey was just slightly brighter than the location of the LDB in the Pleiades. However, they did discover that two of the moderately late (spectral type M5) cluster members (namely HHJ 339 and HHJ 430) did have strong lithium absorption features. Because many fainter members did not have lithium, those stars could not mark the location of the LDB in the Pleiades unless there was a huge age spread in the cluster. Oppenheimer et al. considered several possible explanations for the two stars with strong lithium, but found none to be compelling. The model with the fewest problems was that the two stars were in fact not members of the Pleiades but were instead members of a young moving group that happen to lie in our line of sight to the Pleiades at the current

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[12] Based on spectra obtained at the Crossley reflector by K. Hunger, while he was visiting Lick Observatory and working with G. Herbig, as reported in the 1957 Annual Report of Lick Observatory—Shane, C.D. 1957, AJ 62, 294.

time. No subsequent paper has attempted to more definitively explain the abundant lithium in the spectra of these two stars.

With the new evidence now available, we demonstrate that these two stars are indeed foreground to the Pleiades and that their properties are most consistent with membership in the 32 Ori moving group (Bell et al. 2017). In Section 2, we discuss the new data that we utilize in this paper. In Section 3, we use Gaia DR2 parallaxes and proper motions and our new radial velocities to show that the two stars are definitely not members of the Pleiades. In Section 4, we discuss the K2 light curves for the two stars, and argue that the light curve for HHJ 339 suggests that it is younger than the Pleiades. In Section 5, we show that HHJ 339 and 430[13] are likely members of the 32 Ori moving group based on their Gaia properties and the other data we present.

2. Data Used in This Paper

We use member lists for the 125 Myr old Pleiades cluster, the ∼25 Myr old 32 Ori moving group, the Group 29 moving group (Oh et al. 2017; Luhman 2018), and the ∼3 Myr old Taurus star-forming group in several of the plots we will show. These membership lists are not intended as the complete set of members, but are instead representative subsets of the members of those groups (selected because they have particularly accurate radial velocities in the literature or because they have particularly accurate astrometry). The Pleiades list comes from the Gaia DR2 paper providing membership and HR diagram morphologies for all the nearby open clusters (Gaia Collaboration et al. 2018a). The radial velocities we use for the Pleiades come from Mermilliod et al. (2009). The member list for Group 29 comes from Oh et al. (2017) and the member list for the 32 Ori group comes from Bell et al. (2017). The Taurus member list is based on Rebull et al. (2020), which in turn heavily relies on the list from Luhman (2018) and Esplin & Luhman (2019), and the Taurus radial velocities are from Galli et al. (2019).

The Pleiades was observed by K2 (Howell et al. 2014) during Campaign 4. Processed light curves from that campaign were produced by several groups (as described in Stumpe et al. 2012; Vanderburg & Johnson 2014; Aigrain et al. 2017; Cody & Hillenbrand 2018). Rebull et al. (2016) used light curves from all of those sources (selecting the best light curve for each star from among the several choices) to determine rotation periods for all probable and possible members of the Pleiades. Light curves for both HHJ 339 and 430 were included in that analysis. In Rebull et al. (2016), HHJ 430 was ultimately considered to be a nonmember of the Pleiades based on its location in the color–magnitude diagram (CMD) relative to true Pleiades members; HHJ 339 was categorized as a possible but lower quality member (Bouy et al. 2015 reached essentially the same conclusions regarding these two stars). In Section 4, we provide a detailed discussion of the K2 light curves of both stars. The relevance of those light curves is primarily in that some light-curve morphologies occur only in young stars, and their presence (or absence) in the two HHJ stars could therefore help determine whether membership in the Pleiades is likely or not.

We obtained new Keck High Resolution Echelle Spectrometer (HIRES) spectra for both HHJ 339 and 430 in 2013 December. The spectra cover $\lambda\lambda$4800–9200 Å, at an average resolution of about $R = 50{,}000$ and typical signal-to-noise ratio per pixel of about 30. A description of the data reduction procedures and the process to determine radial velocities and $v\sin i$ values can be found in David et al. (2019). From this analysis, we get RV $= 11.3 \pm 5$ km s^{-1} and $v\sin i = 45$–55 km s^{-1} for HHJ 339, and RV $= 15.8 \pm 5$ km s^{-1} and $v\sin i = 50$–55 km s^{-1} for HHJ 430. Oppenheimer et al. reported slightly higher $v\sin i$ (58 and 65 km s^{-1} for HHJ 339 and 430, respectively) and slightly lower radial velocities (9.4 and 9.1 km s^{-1} for HHJ 339 and 430, respectively), based on their HIRES spectra, with quoted uncertainties of 5 km s^{-1} for each of the radial velocity and $v\sin i$ values. Figure 1 shows snippets from the two spectra centered on Hα and on the Li I λ6708 Å region. The Li I equivalent widths from our spectra (0.61 Å for HHJ339 and 0.63 Å for HHJ 430) are consistent with those reported by Oppenheimer et al.; the Hα profiles and equivalent widths are consistent with those expected for young, active, relatively late-type dMe stars.

High-resolution images, taken with the lucky imaging technique, were obtained with the Calar Alto 2.2 m telescope and the Astralux instrument during the night of 2015 November 20 in order to obtain diffraction-limited images within the $24'' \times 24''$ field of view. We used the AstraLux pipeline (see Hormuth et al. 2007) to perform the basic reduction and co-addition of our lucky imaging frames. The lucky imaging for both stars showed no evidence of any companion, with a limit of about $\Delta m \sim 6$ mag at $0\farcs3$ in each case.

The Gaia DR2 data release (Gaia Collaboration et al. 2018b) provides by far the most accurate parallaxes and proper motions for essentially all of the stars we discuss in this paper. The Gaia photometry (G, B_p, and R_p) for these stars is also the most accurate and homogeneous database from which to construct a CMD for the cluster. We have downloaded the Gaia data from Vizier for all of the Pleiades members identified in the DR2 HR diagram paper, as well as for the Taurus and young moving group members we have investigated to help establish the true lineage of HHJ 339 and 430. In the next section, we use these data as the primary evidence that the two HHJ stars are, in fact, not Pleiades members.

3. Implications from Gaia DR2 Data and the Measured Radial Velocities

The Gaia DR2 data definitively resolved the Pleiades distance controversy (van Leeuwen 2009; Abramson 2018), placing the Pleiades at a mean distance of 135 pc (Lodieu et al. 2019), and not at the ∼120 pc distance that had been inferred from Hipparcos data. The Gaia release also provides the best resource from which to determine whether HHJ 339 and 430 are Pleiades members or not.

Figure 2 shows the location in the sky of HHJ 339 and 430 in relation to the known members of the Pleiades. Both stars are seen in projection to be relatively close to the center of the cluster. The tidal radius of the Pleiades has been estimated as ∼16 parsecs (Raboud & Mermilliod 1998). When projected onto the sky, that tidal radius would lie entirely outside the region shown in Figure 2. More than 300 of the ∼1300 Gaia DR2 Pleiades members lie further from the cluster center as projected on the sky than do HHJ 339 and 430. Therefore, there is nothing in the sky-projected spatial location of HHJ 339 and 430 that argues against membership in the Pleiades.

Figure 3(a) provides a visual comparison of the parallaxes for HHJ 339 and 430 relative to all of the high-quality members

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[13] In SIMBAD, these stars are referred to as Cl* Melotte 22 HHJ 339, for example.

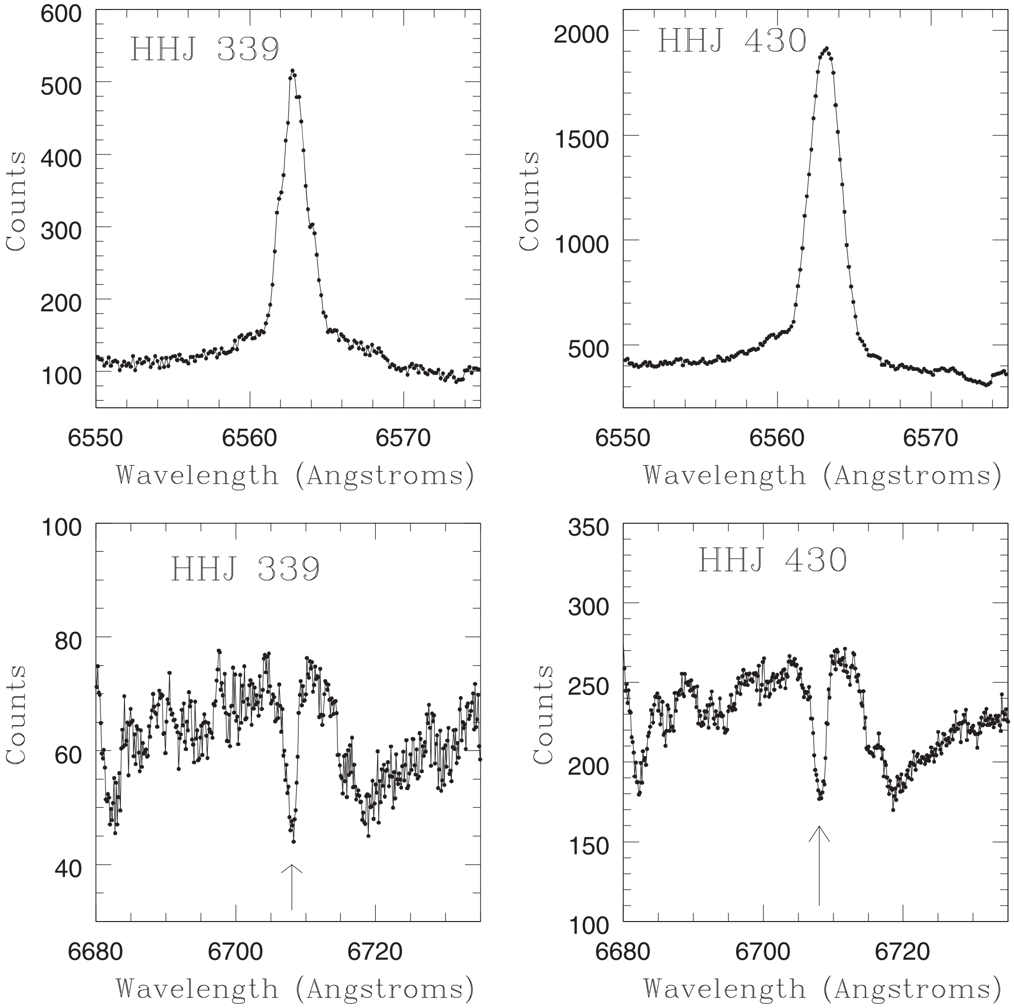

Figure 1. (top) HIRES spectra showing the Hα emission profiles for HHJ 339 and 430; (bottom) Keck HIRES spectra showing the Li I 6708 spectral region for the two HHJ stars. The arrow marks the location of the lithium doublet.

of the Pleiades identified using the DR2 data release. With parallaxes larger than 10 mas, both HHJ 339 and 430 are much closer to us than the true Pleiades members. The median uncertainty in the parallax for the Pleiades members is 0.1 mas yr^{-1}; for the two HHJ stars, the median parallax uncertainty is a bit larger but still less than 0.2 mas yr^{-1}. The two HHJ stars are displaced to the foreground of the Pleiades by about 40 parsecs, placing them well outside the tidal radius of the cluster.

Figure 3(b) shows a vector-point diagram for the Pleiades members again using the Gaia DR2 data, and again highlighting the positions of the two lithium-rich M dwarfs. The true Pleiades members have proper motions centered near 20 mas yr^{-1} in R.A. and -45 mas yr^{-1} in decl. The HHJ stars have proper motions in R.A. that are about 10 mas yr^{-1} larger than the mean Pleiades motion, much greater than the <0.5 mas yr^{-1} proper-motion uncertainties typical of all the stars plotted here. At Pleiades distance, 10 mas yr^{-1} corresponds to about 7 km s^{-1}, which is much larger than the $\sim$0.8 km s^{-1} internal velocity dispersion of the Pleiades (Galli et al. 2017).

Figure 3(c) shows a Gaia-based CMD for the Pleiades, and the locations of HHJ 339 and 430 in that diagram. Both of the HHJ stars are displaced above the single star locus by more than 1.5 mag, hence above where even a triple system composed of equal-mass stars could be. Both of the Oppenheimer stars must therefore be significantly younger than 125 Myr.

Thus by every quantitative measure using the Gaia DR2 data, HHJ 339 and 430 are demonstrably not Pleiades members. Based on our own HIRES spectra as well as that from Oppenheimer et al. (1997), both stars do have nearly primordial lithium, which for their Teff implies an age <40 Myr (Baraffe et al. 2015; David et al. 2019). We will attempt to better constrain their ages after a brief digression concerning their photometric variability.

4. Kepler K2 Light Curves

High-precision 70+ day light curves for both HHJ 339 and 430 were obtained during Campaign 4 of NASA's K2 mission. The K2 data for HHJ 430 shows two strong periods, indicating that it is a binary star[14]; the two periods are 0.3446 and 0.3736 days; such short periods would be fairly typical at Pleiades age but atypically short at, for example, the $\sim$8 Myr age of Upper

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[14] G or K dwarfs can have significant latitudinal differential rotation; their light curves can exhibit two well-defined periods if they have spot groups located at widely different latitudes. Fully convective M dwarfs like HHJ 430 are expected instead to have little or no latitudinal differential rotation, and therefore two periods in their periodogram are best interpreted as evidence for the presence of two stars in the system. See Rebull et al. (2016) and Stauffer et al. (2016) for further discussion of this point.

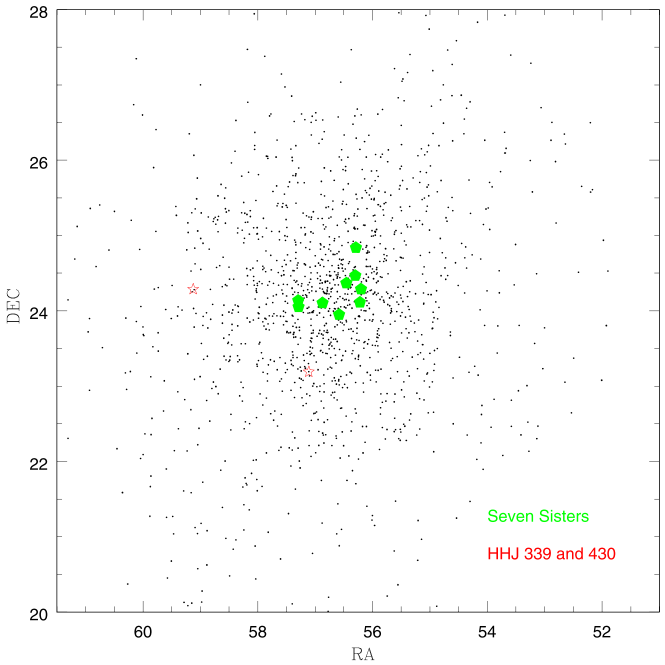

Figure 2. Sky map of known Pleiades members. The Seven Sisters (Alcyone, Merope, Maia, Electra, Sterope, Taygete, and Celaeno) plus their parents (Atlas and Pleione) are highlighted as large, filled circles. HHJ 339 and 430 are shown as red stars. Many low-mass Pleiades members are located outside the region plotted (the tidal radius of the Pleiades when projected onto the sky corresponds to about 7°).

Sco stars (see Rebull et al. 2018). The two periods are quite similar to each other, and the lucky imaging shows that the two stars must also be close to each other spatially. The light-curve morphologies for both components of HHJ 430 (shown in Figure 15 of Rebull et al. 2016) are typical of that for rapidly rotating M dwarfs, where the variability is due to cool starspots. However, this light-curve morphology puts little quantitative constraint on the age of HHJ 430.

By contrast, the K2 light curve for HHJ 339 shows a feature that is very distinctive, and which has at least the potential to place a reasonably quantitative constraint on its age. Figure 4 shows the K2 light curve for HHJ 339, phased to its period of 0.4627 day (Rebull et al. 2016). Based on our visual examination of thousands of K2 light curves, the entire shape of this light curve seems unusual, possibly pointing to something other than non-axisymmetrically distributed spots as the physical mechanism responsible for the photometric variability. However, it is possible that some unusual distribution of spots could more or less explain most of the variability shown in Figure 4. What spots cannot explain, however, is the relatively deep and narrow-in-phase flux dip centered near phase 0.75. As argued in a number of papers (David et al. 2017; Stauffer et al. 2017; Zhan et al. 2019), flux dips such as this are most likely due to dust "clouds" orbiting at the Keplerian corotation radius that pass through our line of sight to the star. The variability of the shape of the dip on timescales less than a K2 campaign length (~75 days)—see Figure 4—is typical of some of these stars, including RIK-210 (David et al. 2017) and a few of the other pre-main-sequence (PMS) M dwarfs in Upper Sco (Stauffer et al. 2017, 2018). Such narrow-in-phase flux dips are very rare or absent at ages older than the Pleiades (Basri & Nguyen 2018; Rebull et al. 2018). With existing data, it is not yet possible to place a quantitative age constraint on HHJ 339 based on the presence, depth, and shape of its narrow flux dip, but by combining data from K2, the Transiting Exoplanet Survey Satellite (TESS), and Gaia for open clusters and moving groups of a variety of ages, such a quantitative age constraint may become possible.

By combining the $v \sin i$, rotation period, and the position of HHJ 339 in an HR diagram, we can estimate the inclination angle of the star's rotational axis. To convert the photometry and spectral type information for HHJ 339 into luminosity and effective temperature, we adopt the data tables in Pecaut & Mamajek (2013, hereafter PM13). In order to use those tables, however, we need a rough estimate of the true age of HHJ 339. In the next section, we will adopt an age of 25 Myr for HHJ 339, which implies we should use Table 6 of PM13 to provide the correlation between $V - K_s$ color or spectral type and $T_{\rm eff}$, and the bolometric correction appropriate for that $T_{\rm eff}$. We adopt $V = 17.45$ from (Kamai et al. 2014), and $J = 12.164$ and $K_s = 11.32$ from the Two Micron All-Sky Survey (Skrutskie et al. 2006). Adopting $A_V = 0.12$, this yields $(V - K_s)_o = 6.02$, from which Table 6 of PM13 yields $T_{\rm eff} = 2900$ K and $BC_J = 2.00$. Combining those numbers with the Stefan–Boltzmann equation then yields $R = 0.48\,R_\odot$. Combining this with the measured period and the average of our $v \sin i$ estimate and Oppenheimer's, we derive $\sin i = 1.0$, and hence that the system inclination is near 90°. This is roughly as expected for a model where the occulting material is in a plane located between the equatorial rotation plane and the equatorial plane of the star's dipole magnetic field (Jardine et al. 2020).

5. Age and True Lineage of HHJ 339 and HHJ 430

The preceding section provides strong evidence that HHJ 339 and 430 are not members of the Pleiades, and are in fact foreground to the Pleiades and much younger. Can we accurately determine the age of these two stars and learn something of their true origin?

There is a long and at times contentious history concerning the age spread within the Taurus SFR and/or the presence and extent of a relatively young moving group population toward the general direction of Taurus. Wichmann et al. (1996) identified a set of more spatially extended, apparently slightly older low-mass PMS stars in the general direction of Taurus and posited that they were real members of the Taurus SFR and therefore evidence for a significant age spread. Briceno et al. (1997) instead argued that the older, more extended population of stars were members of one or more moving groups seen in projection toward the Taurus SFR but not natally connected to it. Dozens of papers have been published arguing this issue since the 1990s. The Gaia DR2 data offer the possibility to at least largely settle the issue (Luhman 2018; Kraus et al. 2019). Based on a lengthy analysis of the DR2 data and other published sources, both Luhman and Kraus et al. concluded that the more spatially extended population most probably represents a previous generation of star formation, unconnected to the ~3 Myr old Taurus SFR population. Group 29 (Oh et al. 2017) and the 32 Ori Group (Bell et al. 2017) have space motions, ages, and spatial distributions that make them likely contributors to the older-but-still-young spatially extended population of stars toward Taurus. We compare the properties of HHJ 339 and 430 to the members of Group 29, the 32 Ori Group, and Taurus in the following plots.

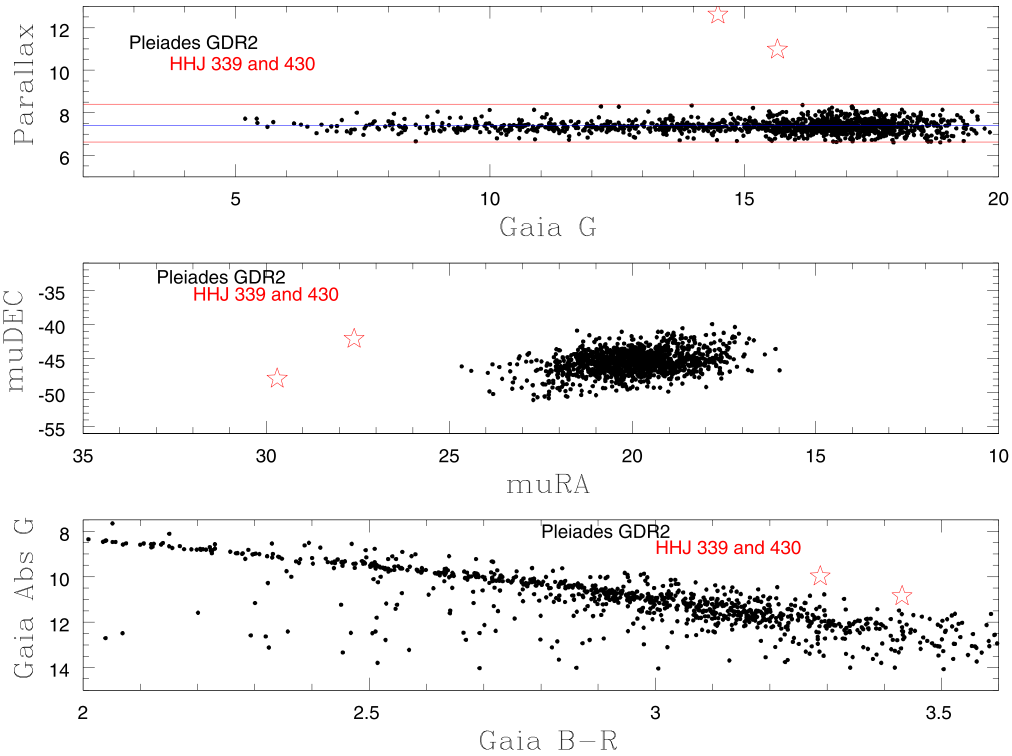

Figure 3. (a) Gaia DR2 parallaxes of the Pleiades members plotted vs. their Gaia *G* magnitude. Red stars show the same data for the two lithium-rich M dwarfs HHJ 339 and 430. The blue horizontal line marks the mean parallax of the Pleiades; the two red horizontal lines denote the tidal radius of the cluster. (b) Gaia DR2 proper motions for Pleiades members. The two HHJ stars are again shown as red stars. (c) Gaia-based CMD for the Pleiades members plus the two lithium-rich M dwarfs. In all three diagrams, the DR2 uncertainties in the plotted quantities for HHJ 339 and 430 are much smaller than the size of the star symbol used to mark their location. The two HHJ stars are strong outliers in all three diagrams and are clearly not Pleiades members.

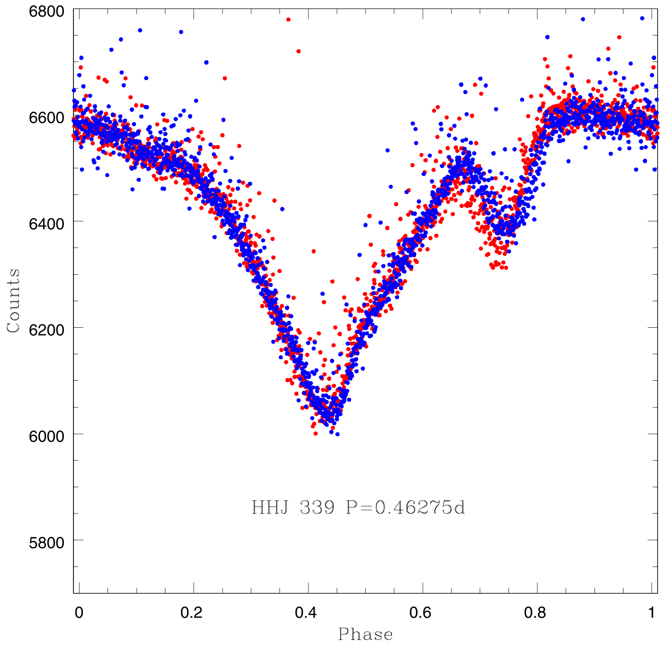

Figure 4. K2 light curve for HHJ 339, phased to its rotation period of $P = 0.4627$ days. Blue points indicate data in the first half of the K2 campaign period; red points indicate data taken during the second half of the campaign. The shape of the narrow flux dip at phase ∼0.75 changes between the two time periods, whereas the rest of the light-curve morphology remains nearly constant over the whole K2 campaign. Narrow flux dips like this are only present in the optical light curves of young, low-mass stars.

Figure 5 shows space motions of the two Oppenheimer lithium-rich M dwarfs compared to that of members of the other young stellar groups that populate our line of sight toward Taurus. We have used the website (http://kinematics.bdnyc.org/query) to convert measured proper motions, radial velocities, positions, and distances to *UVW* space motions (Rodriguez 2016); for the radial velocities of the HHJ stars, we adopt the average of our values and those of Oppenheimer et al. (1997). The space velocity plots show that when accurate input data are used, the space motions of HHJ 339 and 430 are inconsistent with Pleiades membership and also with membership in Group 29. Their space motions are most consistent with that of the 32 Ori group.

In Figure 3(c), we showed that HHJ 339 and 430 had locations in a Gaia-based CMD that were incompatible with membership in the Pleiades (they are both too bright for their $B_p - R_p$ color). Figure 6 shows another CMD, this time plotting probable members of the 32 Ori and Group 29 moving groups along with the two HHJ lithium-rich M dwarfs. The two moving groups appear to have quite similar isochronal ages; both moving groups have estimated ages of about 25 Myr (Bell et al. 2017; David et al. 2019). The two Oppenheimer stars have locations in this CMD consistent also with that age.

Table 1 shows the mean space motions of the systems we have discussed, as well as that for the Beta Pic moving group (BPMG). The table again shows that the space motions of HHJ 339 and 430 are best aligned with that for the 32 Ori moving group. However, given the ∼3.5 km s^{-1} uncertainty in the radial velocity for the HHJ stars, membership in the BPMG cannot be excluded. The age estimated for the BPMG ranges from 10 to 30 Myr, but has recently been reported to be near 20–25 Myr (Binks & Jeffries 2014; Mamajek & Bell 2014; Bell et al. 2015), and so is quite similar to that for the 32 Ori moving group.

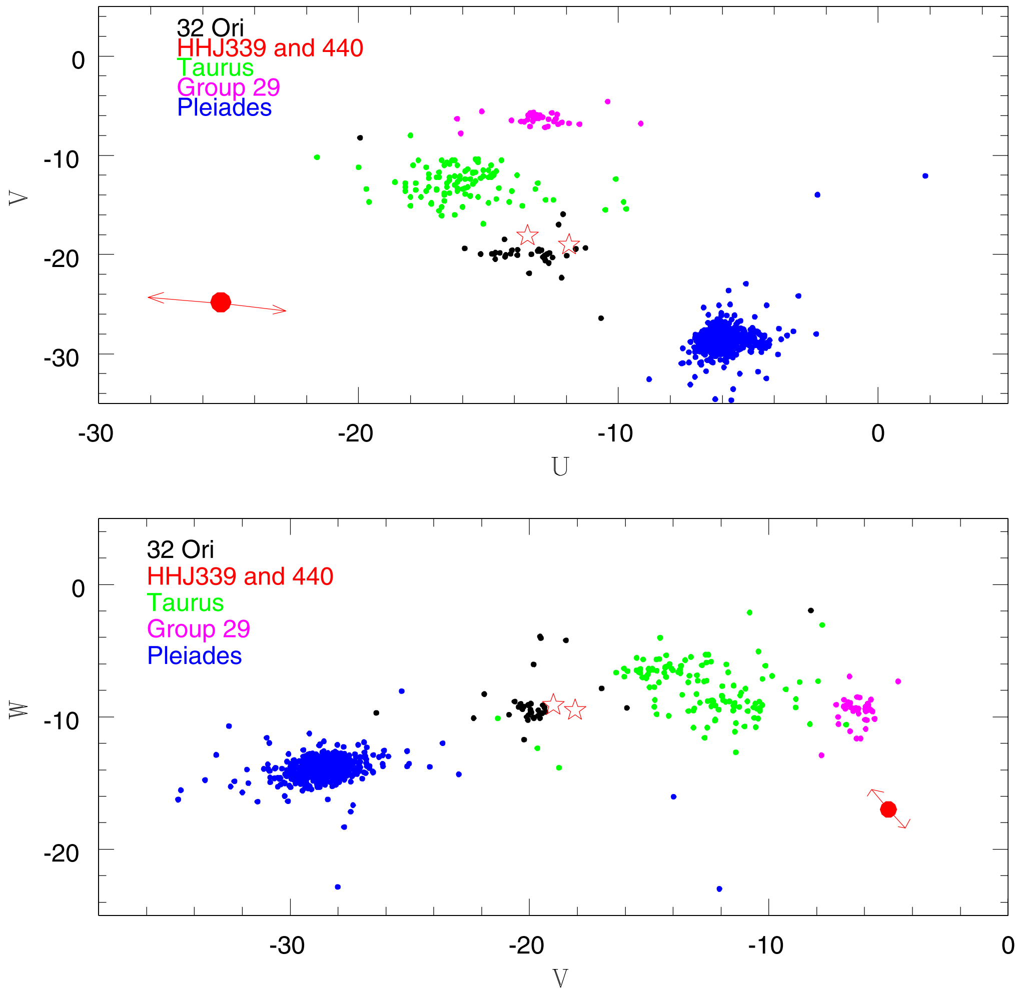

Figure 5. Space motion plots for the lithium-rich M dwarfs HHJ 339 and 430 compared to other kinematic groups known to be present in the general direction of K2 fields 4 and 13. By far the largest source of uncertainty in the UVW motions of HHJ 339 and 430 are the ~3.5 km s^{-1} uncertainties in their radial velocities. The red dot and associated arrows in each figure show the impact of the 1σ uncertainty in radial velocity on their derived *UVW* motions. The two HHJ stars have kinematics that are quite disparate from the Pleiades, but are most compatible with the 32 Ori moving group.

Table 1
Space Motions of Systems Relevant to This Paper

ID	*U* (km s^{-1})	*V* (km s^{-1})	*W* (km s^{-1})
Pleiades	−6.2	−28.7	−14.7
Taurus SFR	−14.3	−9.3	−8.8
32 Ori group	−12.8	−18.8	−9.9
Group 29	−13.	−6.	−9.5
HHJ 339	−11.8	−19.0	−9.1
HHJ 430	−13.5	−18.1	−9.5
Beta Pic MG	−10.9	−16.0	−9.0

6. Discussion and Conclusions

The Pleiades is the most intensively studied open cluster in the sky. Its membership list is correspondingly quite heavily vetted, with very few stars whose membership were greatly in debate even prior to the advent of space-based astrometric missions. HHJ 339 and 430 were exceptions to that rule. They had been identified as probable Pleiades members based on their proper motions. They had independently been identified as young dM stars seen in the direction of the Pleiades based on the fact that they are both flare stars and strong X-ray sources, criteria that in most cases successfully selects Pleiades members. The fact that their spectra show a nearly primordial lithium abundance therefore came as a surprise. If they were indeed members of the Pleiades, then some exotic physics must be involved (late accretion of large, rocky bodies?) or the Pleiades must contain an admixture of stars much younger than the main population. If they are not members of the Pleiades, then there must be a previously unsuspected population of young stars projected onto the face of the Pleiades.

Publication of the Gaia DR2 catalog has provided the resolution to this conundrum. The proper motions of HHJ 339 and 430, while similar to that of Pleiades members, are inconsistent with Pleiades membership when measured to the accuracy provided by the DR2 data. Both stars are also significantly foreground to the Pleiades based on the exquisite DR2 parallaxes. When combined with radial velocities from Keck HIRES spectra, we find that HHJ 339 and 430 have space motions that match that of the 32 Ori moving group. They also have photometry that matches that of previously identified 32 Ori members when a Gaia-based CMD is constructed. At the estimated age of 25 Myr ascribed to the 32 Ori group, models predict that stars with M5 spectral type should retain nearly

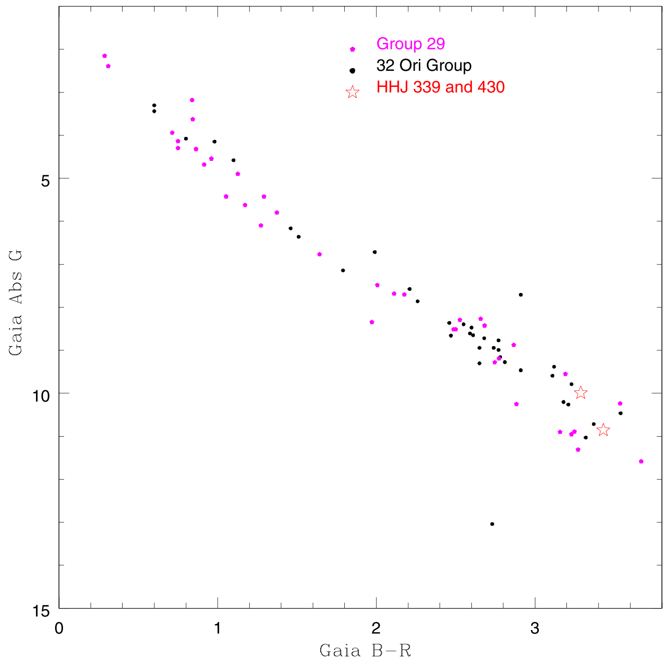

Figure 6. Gaia-based CMD for the members of the 32 Ori group and the two Oppenheimer lithium-rich M dwarfs. The Oppenheimer stars have CMD locations consistent with the 32 Ori group members.

primordial lithium abundance, thereby explaining the original anomaly discovered by Oppenheimer et al (1997).

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