MAGNETIC FIELDS IN M DWARF MEMBERS OF THE PLEIADES OPEN CLUSTER USING APOGEE SPECTRA

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ABSTRACT

Average magnetic field measurements are presented for 62 M-dwarf members of the Pleiades open cluster, derived from Zeeman-enhanced Fe I lines in the H-band. An MCMC methodology was employed to model magnetic filling factors using SDSS-IV APOGEE high-resolution spectra, along with the radiative transfer code SYNMAST, MARCS stellar atmosphere models, and the APOGEE DR17 spectral line list. There is a positive correlation between mean magnetic fields and stellar rotation, with slow-rotator stars (Rossby number, Ro > 0.13) exhibiting a steeper slope than rapid-rotators (Ro < 0.13). However, the latter sample still shows a positive trend between Ro and magnetic fields, which is given by <B> = 1604 × Ro^{−0.20}. The derived stellar radii, when compared with physical isochrones, show that on average, our sample shows radius inflation, with median enhanced radii ranging from +3.0% to +7.0%, depending on the model. There is a positive correlation between magnetic field strength and radius inflation, as well as with stellar spot coverage, correlations that together indicate that stellar spot-filling factors generated by strong magnetic fields might be the mechanism that drives radius inflation in these stars. We also compare our derived magnetic fields with chromospheric emission lines (Hα, Hβ and Ca II K), as well as with X-ray and Hα to bolometric luminosity ratios, and find that stars with higher chromospheric and coronal activity tend to be more magnetic.

Keywords: Near Infrared astronomy(1093) — Open star clusters(1160) — M dwarf stars(982) — Stellar activity(1580) — Stellar magnetic fields(1610)

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1. INTRODUCTION

Quantitative characterization of magnetic fields provides a deeper understanding of stellar physics. As a star evolves, its stellar wind interacts with the magnetosphere, generating a torque that converts kinetic energy into magnetic energy, reducing the stellar angular momentum and resulting in a slowing of its rotational velocity (Kawaler 1988). This process of magnetic braking over time enables gyrochronology to estimate the age of a star based on its stellar rotation (Skumanich 1972; Barnes 2003), with younger stars tending to have higher magnetic fields and activity than older stars of similar T\text{eff}. Another effect caused by magnetic fields is the heating of the stellar chromosphere and coronae, causing the emission of, respectively, strong UV and X-ray non-thermal radiation (Havley et al. 2014; Astudillo-Defru et al. 2017; Newton et al. 2017).

Magnetic fields are especially important in M dwarf stars, as these stars have longer spin-down timescales, maintaining magnetic fields for longer periods than hotter stars (Newton et al. 2016). This means that any surrounding exoplanets will experience high-energy fluxes for longer periods, which can impact the habitability of these systems. In addition, since M dwarfs are cool, their habitable zones are located closer when compared to hotter stars, which increases the incident flux, as well as the probability of orbit locking, which, in turn, also impacts habitability. Nonetheless, M dwarf stars represent around 70% of the stars of our galaxy (Salpeter 1955; Reid & Gizis 1997), and some of them can live trillions of years on the main sequence, which gives life many opportunities and time to form and evolve around these stars. A deep understanding of their magnetic fields and implications for their environment is fundamental for the understanding of these stars and the habitability of their exo-planetary systems.

One method to study stellar magnetic fields is through the Zeeman effect. Magnetically sensitive lines (e.g., having high effective Landé g-factors) when subject to magnetic fields are split into components, which we can observe as an additional line broadening. This broadening scales with the square of the line central wavelength, therefore spectral lines located at longer wavelengths are more sensitive to Zeeman splitting than lines with the same effective Landé-g factors located in the bluer part of the spectrum (see Kochukhov 2021 and references therein).

Due to other broadening mechanisms, such as Doppler broadening, stellar rotation, and instrumental broadening, we may not be able to resolve the Zeeman splitting in the spectrum, and what we measure is the Zeeman intensification of an affected line (Stift & Leone 2003; Basri et al. 1992; Basri & Marcy 1994).

There are two main ways to characterize stellar magnetic fields, one considering large-scale and the other small-scale magnetic fields. Large-scale analyses provide a topological view of the stellar magnetic field, separating it into components based on different orientations. The technique used for this characterization, Zeeman-Doppler Imaging (ZDI, Kochukhov 2016) is based on the analysis of the circular polarization of the line, described by the Stokes V parameter, and therefore spectro-polarimetric data are needed for this technique. The small-scale magnetic approach models the total intensity of the field and is based on the Stokes I parameter, and no polarimetric stellar data are needed. The review by Kochukhov (2021) discusses the current state of M dwarf magnetic field studies and presents a compilation of large and small-scale magnetic field measurements from the literature. Below we mention the results of a few of these studies.

The first work to model the magnetic field for an M dwarf star in the literature was Saar & Linsky (1985), who used Ti I lines from a high-resolution (R\sim45,000) K-band spectrum of the flare star AD Leo and found a mean magnetic field of 3.8 kG. Many works followed, modeling the Zeeman effect in M dwarfs spectral lines in the optical and infrared and finding magnetic fields ranging from zero up to 8 kG (Johns-Krull & Valenti 1996; Shulyak et al. 2011, 2014, 2017, 2019; Reiners et al. 2022; Cristofari et al. 2023a,b; Han et al. 2023). Reiners et al. (2022) determined magnetic fields for a large sample of M dwarfs using CARMENES spectra, and analyzed how magnetic fields are related to parameters such as magnetic flux, activity, and Rossby numbers, and how these distributions change when comparing the saturated and non-saturated regimes. Some works studied magnetic fields deriving large-scale magnetic fields from Stokes V, as well as small-scale fields, and found that the latter is considerably greater than the one obtained from circular polarization, which indicates that most of the star’s magnetic field is probably stored in small structures at its surface (Phan-Bao et al. 2009; Kochukhov & Lavail 2017; Kochukhov & Shulyak 2019; Kochukhov & Reiners 2020).

All of the studies mentioned above explored magnetic fields in M dwarfs from the Galactic field star population and these can in principle have different ages and metallicities. Stars from an open cluster, on the contrary, originate from the same molecular cloud and are expected to have approximately the same age and chemistry, making them great benchmarks with which to study stellar evolution and atomic diffusion, but these are also ex-
cellent benchmarks for studying stellar magnetic fields. Because cluster stars form at the same time and share the same chemical composition, metallicity and age dependencies are removed by their inter-comparison, and this allows for an investigation of magnetic fields primarily as a function of other stellar properties, such as effective temperatures or rotational periods (Souto et al. 2021). The recent work of Wanderley et al. (2023) used APOGEE near-infrared spectra (Majewski et al. 2017; Abdurro’uf et al. 2022) to derive atmospheric parameters and metallicities, and study radius inflation in a sample of M dwarf stars members of the young Hyades open cluster. (Wanderley et al. 2023) found that these stars are on average inflated, and this may be caused by stellar magnetic fields.

In this work, we use spectral lines affected by Zeeman broadening present in the SDSS APOGEE spectra to derive average magnetic fields for a sample of 62 M dwarfs from the young (age = 112 ± 5 Myr; Dahm 2015), near-solar metallicity (Soderblom et al. 2009) Pleiades open cluster. This is the first study to derive magnetic fields for a sample of M dwarf members of an open cluster, and also the first to derive magnetic fields for M dwarfs based on APOGEE H-band spectra.

This paper is organized as follows: Section 2 presents the APOGEE data and sample selection. In Section 3 we present the methodology employed to derive average stellar magnetic fields for the Pleiades M dwarf star sample. In Section 4, we discuss the results which include the relation between magnetic fields and stellar rotation, comparisons with the literature, radius inflation, and analysis of activity indicators. Finally, Section 5 summarizes the conclusions.

2. APOGEE DATA AND SAMPLE SELECTION

We determined average magnetic fields by analyzing near-infrared (λ1.51µm to λ1.69µm), high-resolution (average resolution of R ~ 22,500) spectra of Pleiades M dwarf stars observed by the SDSS IV APOGEE survey (Majewski et al. 2017; Blanton et al. 2017). As part of SDSS IV, the APOGEE spectra analyzed here were obtained at the 2.5-m telescope located at APO in the northern hemisphere (Bowen & Vaughan 1973; Gunn et al. 2006; Wilson et al. 2019).

An initial sample of Pleiades members was obtained from Heyl et al. (2022) and confirmed using the membership analysis in Cantat-Gaudin et al. (2020). We adopted a threshold of 80% of minimum membership probability from Cantat-Gaudin et al. (2020) for a star to be considered a member of the Pleiades. We cross matched this sample with APOGEE DR17 (Abdurro’uf et al. 2022), and selected for M dwarfs with 4.7 < $M_K_s$ < 6.2 (Mann et al. 2015, 2016), using 2MASS $K_S$ magnitudes (Skrutskie et al. 2006) and distances from Baier-Jones et al. (2021). All magnitudes were corrected for extinction using the mean extinction to the Pleiades of $A_V = 0.12$ (Stauffer et al. 2007), and the relations from Wang & Chen (2019). To remove binary stars from the sample, we considered only stars with a scatter in APOGEE radial velocity smaller than 1 km s$^{-1}$. We also removed stars that presented large Gaia DR3 (Gaia Collaboration 2022) RUWE numbers (RUWE > 1.4), as this can indicate the presence of an unresolved companion (Belokurov et al. 2020). In addition, stars without a vsin$i$ measurement in DR17 were also removed from the sample.

We also analyzed the distribution of distances, proper motions (Gaia DR3, Gaia Collaboration 2022), and radial velocities (from APOGEE DR17) of the selected targets to check for outliers, but we found none. Finally, we also removed from the sample stars that had noisy and problematic APOGEE spectra. Our final sample of Pleiades members analyzed in this study is composed of 62 M dwarfs.

Figure 1 presents the Gaia and 2MASS CMDs (color-magnitude diagram) of the selected targets (top panels), their distribution in space, and proper motions (middle panels), as well as histograms for their star distances (d), and radial velocities (RV) (bottom panels). The average distance, radial velocity, and proper motions along α (right ascension) and δ (declination) for our Pleiades M dwarf sample are, respectively: <d>=135.12±2.19 pc, <RV>=5.86±2.19 km s$^{-1}$, < $\mu_\alpha \cos \delta$ >=18.20±0.97 mas yr$^{-1}$ and < $\mu_\delta$ >=−45.35±1.10 mas yr$^{-1}$. These results are in good agreement with measurements from Lodieu et al. (2019) of respectively: 135.15±0.43 pc, 5.67 ± 2.93 km s$^{-1}$, 19.5 mas yr$^{-1}$ and −45.5 mas yr$^{-1}$.

In the top panels of Figure 1 we show several isochrones from the literature: a MIST isochrone (Choi et al. 2016), a DARTMOUTH isochrone (Dotter et al. 2008), a PARSEC isochrone (Bressan et al. 2012; Nguyen et al. 2022), a BHAC15 isochrone (Baraffe et al. 2015), and two SPOTS isochrones from Somers et al. (2020), one with spots covering 20% of the stellar photosphere and another with a spot coverage of 80%. All isochrones shown are for solar metallicity and an age of 100 Myr, which is roughly the estimated age for the Pleiades open cluster.

The Pleiades study by Covey et al. (2016) found significant scatter in the K vs J–K diagram of Pleiades stars (see Figure 3 in their paper). That study also compared the observed colors of Pleiades stars with physical models and found that the V–K colors in rapidly rotating stars present a positive offset for the same V
magnitude if compared to slow rotators, which was inter-
terpreted as being due to binarity or a dependency of
photospheric/spot properties on rotation rate. The pho-
tometric data in the Gaia G vs G\textsubscript{RP}−G\textsubscript{BP} CMD, shown
in the top left panel of Figure 1, shows a clear offset,
with most isochrones that do not consider stellar spots
presenting bluer colors for the same magnitudes, while
the SPOTS isochrone associated with an 80% photos-
pheric spot coverage presents an excellent match to the
photometric data of the selected stars. We note that
this pattern is not seen in the 2MASS CMD, where all
isochrones present very small variations, even for differ-
ent spot fractions, which might be related to the lower
photometric spot contrast in the infrared when com-
pared to the visible spectrum.

3. METHODOLOGY AND RESULTS

To derive average magnetic fields from Zeeman intens-
ified lines we used the APOGEE line list (Smith et al.
2021) and model atmospheres from the MARCS grid
(Gustafsson et al. 2008). The average magnetic field
modeling in this study was done using the SYNMAST
spectral synthesis code (Kochukhov et al. 2010), which
computes the effects of magnetic fields on stellar spectra.
This code uses polarised radiative transfer calculations
to derive IQUV local Stokes parameters for a given mag-
netic field vector (in radial, meridional, and azimuthal
orientations). In this study, we assumed a radial mag-
netic field and used SYNMAST to calculate intensity at
seven limb angles. Then another code was used to per-
form disk integration, converting these intensity fluxes
into density fluxes, which can be compared to APOGEE
spectra.

To search for the best iron lines in the APOGEE re-
region that can be used as magnetic field indicators for
M dwarf stars, we compared two SYNMAST syntheses,
one computed for 0 kG (no magnetic field) and
another for 3 kG. We selected four Fe I lines as best
indicators: \(\lambda 15207.526 \text{ Å}, \lambda 15294.56 \text{ Å}, \lambda 15621.654 \text{ Å},\)
and \(\lambda 15631.948 \text{ Å} \). Table 3 presents the selected spectral
lines, their central wavelengths in vacuum, the excita-
tion potentials, \(\log gf\) values from the APOGEE line list
(Smith et al. 2021), effective Landé-g factors collected
from VALD database (Piskunov et al. 1995; Kupka et al.
1999), as well as term designations associated with the
upper and lower energy levels. The four selected Fe I
lines are considerably sensitive to magnetic fields pre-
senting effective Landé-g factors that range between
\(\sim 1.5\) and \(\sim 1.7\). All the selected Fe I lines, except
\(\lambda 15621.654 \text{ Å}\) are from the same multiple. These lines
were used to compute the magnetic fields for all stars in
our sample and gave overall consistent results.

After the selection of diagnostic lines for measuring
magnetic fields, the next step in our analysis was to
generate a grid of synthetic spectra which was used in
the analysis of each star. We adopted the DR17 ASP-
CAP (APOGEE Stellar Parameter and Chemical Abund-
dances Pipeline, García Pérez et al. 2016; Abdurro’uf et al.
2022) \(T_{\text{eff}}\) values for each star, along with an ap-
proximate \(\log g\) \((\sim 4.7 – 4.8)\), depending on the stellar
\(T_{\text{eff}}\). The ASPCAP results used in this work were com-
pared with the Turbospectrum (Plez 2012) code instead
of Synspec (Hubeny & Lanz 2011), however, we note
that there are no significant differences between both
sets of results for M dwarfs. The spectra of M dwarfs
are relatively insensitive to the microturbulent velocity
parameter, as noted by Souto et al. (2017, 2020), who
found that a value of 1 km s\(^{-1}\) provides good fits to
the observations, and we adopt this value in our analy-
sis. All measurable Fe I lines in the APOGEE spectra of
M dwarfs have high effective Landé-g factors, which
makes them not suitable to be used as rotational broad-
ening indicators. Therefore, we used a sample of OH
lines, which are insensitive to magnetic fields. This ap-
proach is similar to the one adopted by Johns-Krull
et al. (2004); Johns-Krull (2007); Yang et al. (2008);
Yang & Johns-Krull (2011); Lavail et al. (2019), who
derived mean magnetic fields for T-Tauri stars from K-
band near-infrared spectra, using magnetically insensi-
tive CO lines to measure non-magnetic broadening.
To derive projected rotational velocities (\(v\sin i\)) for the stars
we used the radiative transfer code Turbospectrum (Plez
2012); we adopted \(v\sin i\) threshold of 3 km s\(^{-1}\) given the
spectral resolution of the APOGEE spectra. We com-
puted a grid of synthetic spectra, for the adopted stellar
parameters for each star and Fe I line, with metalliciti-
ies ranging from \(-0.75 \leq [\text{Fe/H}] \leq 0.5\) in steps of 0.25,
and magnetic field values from 0 to 12 kG in steps of
2 kG, considering only the radial component. We then
convolved the synthetic spectra with a rotational pro-
file for the adopted \(v\sin i\) as well as a Gaussian profile
 corresponding to the spectrum LSF (see Wilson et al.
2019; Nidever et al. 2015). Each synthesis was fitted to
the DR17 normalized APOGEE spectrum (García Pérez
et al. 2016) and was subject to small wavelength shifts
when needed.

We employed Monte Carlo and Markov Chain
(MCMC) to model the observed spectra and derive
magnetic fields for the Pleiades M dwarfs. MCMC is
a powerful tool, not only because it provides best fits
to observations but also because it gives realistic and
well-defined uncertainties based on the posterior distri-
bution. Our methodology considers that the surface of
the star can be divided into different components, each
Figure 1. From left to right, the top panels present respectively Gaia and 2MASS CMDs, the blue points are the selected M dwarf members of the Pleiades open cluster. Several 100 Myr solar metallicity isochrones are shown: MIST, DARTMOUTH, PARSEC, BHAC15, and SPOTS. Two SPOTS isochrones are shown, one for a photosphere spot coverage of 20% and another for 80%. The middle panels present respectively the distribution in space (right ascension and declination) and proper motions (from Gaia DR3) of the target stars. The bottom panels present respectively the distance (Bailer-Jones et al. 2021) and radial velocity histograms. The middle and bottom panels also present the mean and standard deviations for the parameters.

Note that the non-magnetic filling factor $f_0$ is given by $1 - \sum f_n$. For each entry in the posterior distribution, we calculate an average magnetic field in Gauss units given by:

$$< B > = \sum_n f_n \times 1000^n , \quad n = [2, 4, 6, 8, 10, 12]$$

The adopted average magnetic field, along with the lower and upper uncertainties, are given respectively by the median, the 16th, and 84th percentiles of the posterior distribution. In Table 1 we provide the filling factors associated with a different magnetic field value. The filling factor describes the fraction of the stellar surface associated with a specific $<B>$. Many works in the literature used MCMC to derive average magnetic fields from filling factor determinations (Lavail et al. 2019; Kochukhov & Reiners 2020; Hahlin et al. 2021; Hahlin & Kochukhov 2022; Reiners et al. 2022; Cristofari et al. 2023a,b; Hahlin et al. 2023; Pouilly et al. 2023).

We developed a methodology to derive magnetic fields, that employs the python-code emcee (Foreman-Mackey et al. 2013) and finds the combination of metallicity, and 6 filling factors (2–12 kG in a 2 kG step) that best fits the four selected Fe I lines at the same time. We note that the non-magnetic filling factor $f_0$ is given by $1 - \sum f_n$. For each entry in the posterior distribution, we calculate an average magnetic field in Gauss units given by:

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and mean magnetic fields for two stars, the ones having the highest and lowest $<B>$ in our sample.

In Figure 2, we illustrate the methodology by presenting the best fits, as well as the corner plot for the star 2M03511207+2355575. The left panels show fits for the four lines, where black dots are the observed spectrum, and the blue and red lines represent respectively the synthesis with the derived magnetic field, and the result with the same metallicity but no magnetic field. The right panel shows the corner plot describing the results. It presents the median and uncertainties (from 16th and 84th percentiles) of the modeled filling factors and the metallicity. We also show the posterior distribution for the derived average magnetic field.

The derived mean magnetic fields for the studied Pleiades M dwarf stars range from $\sim$1.0 to $\sim$4.2 kG, with a median±MAD of 3.0±0.3 kG. Table 2 presents the derived mean magnetic fields for the sample stars, along with the adopted $T_{\text{eff}}$ and $v\sin i$, and the SNR of the APOGEE spectra analyzed. This table also contains some quantities that will be discussed in Section 4: rotational periods, and Rossby numbers the ratio between the derived magnetic fields and the magnetic field limit based on kinetic-to-magnetic energy conversion, magnetic fluxes, and activity indicators: X-ray to bolometric fluxes, and activity indicators: X-ray to bolometric.

The Rossby number (Ro) is an important indicator of stellar activity, it is given by the ratio between the rotational period and the convective turnover time. The stellar activity, it is given by the ratio between the rotational period and the convective turnover time. The rotational periods of the sample stars include both slow and rapid rotators, encompassing rotational periods $\sim$0.7 to 17.3 days.

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4. DISCUSSION

4.1. Magnetic Fields, Rossby Numbers and Stellar Rotation

We collected rotational periods for 53 stars in our sample from the works by Hartman et al. (2010), Rebull et al. (2016) and Covey et al. (2016), who analyzed data respectively from the HATNet (Bakos et al. 2004), K2 (Howell et al. 2014), and PTF (Law et al. 2009; Rau et al. 2009) surveys. The rotational periods of the sample stars include both slow and rapid rotators, encompassing rotational periods $\sim$0.7 to 17.3 days.

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The mean magnetic fields derived for the sample stars versus their projected rotational velocities, $v\sin i$ (both of which are quantities derived from the APOGEE spectra), are shown in Figure 3 as blue symbols. The blue circles represent stars for which we can estimate the $v\sin i$, while the blue triangles are stars having $v\sin i$ values up to 3 km s$^{-1}$, the adopted threshold in $v\sin i$ that can be estimated in this study. We also show in this figure literature results from R22 as black x’s. The mean magnetic fields for the Pleiades stars generally overlap with the M dwarfs in R22 within the overlapping $v\sin i$ range, showing just a small systematic difference in $<B>$ when compared to R22.

Figure 4 shows our results of magnetic fields versus rotational periods for the Pleiades M dwarfs (red and blue open circles), along with results from the literature for comparison. We compiled a total of 281 average magnetic field measurements from the literature. The results from Shulyak et al. (2017) and Shulyak et al. (2019) are represented by green squares in Figure 4. Results from Cristofari et al. (2023a) and Cristofari et al. (2023b), (results from radial-tangential macroturbulent velocity profiles and fitted log$g$) are represented by cyan diamonds. Results from R22 are for stars with $T_{\text{eff}} < 4000$ K and are represented by black x’s. Finally, other results from the literature (orange triangles), are from the following works: Shulyak et al. (2011); Kochukhov & Lavail (2017); Kochukhov et al. (2001, 2009); Kochukhov & Shulyak (2019); Johns-Krull & Valenti (2000); Afram et al. (2009); Shulyak et al. (2014); Saar & Linsky (1985); Saar (1994); Phan-Bao et al. (2009); Saar (1996); Johns-Krull & Valenti (1996).

We can divide the $<B>$–$P_{\text{rot}}$ plane in Figure 4 into two regions that correspond to the saturated and unsaturated regimes. Red and blue open circles in this figure represent respectively stars in our sample that are slow rotators (Ro$>$0.13, non-saturated regime) and rapid rotators (Ro$<$0.13, saturated regime). We added a vertical dashed line at $P_{\text{rot}}$=7 days to Figure 4, which is an estimated threshold analogous to the separation based on Rossby numbers. Stars in the non-saturated regime are expected to have lower activity levels and also to present a greater dependency between Rossby numbers and magnetic fields. Stars in the saturated regime are in the limit of kinetic to magnetic energy conversion, and show a much flatter relation, although there
is still some dependency between Rossby numbers and magnetic fields.

Most of the stars in our sample have rotational periods roughly between 1 and 10 days. Overall, stars in the saturated regime (blue open circles) follow an approximately constant $<B>$ as a function of $P_{\text{rot}}$, showing just a modest inclination in the trend. It is clear that our results for this population overlap with results from the literature in this regime. For sample stars in the unsaturated regime (open red circles), $<B>$ values begin to show a de-saturation signal (at $P_{\text{rot}} \sim 7$ days), with the slowest rotating stars of our sample presenting a steeper negative relation between rotational periods and magnetic fields than for faster rotators. Although our sample does not include very slowly rotating stars, our results generally overlap with literature values and are in line with the steep relation between magnetic fields and rotational periods in the literature, which extends to $P_{\text{rot}} \sim 100$ days. It is interesting to note that despite the fact that our sample and that from R22 both have the same upper $T_{\text{eff}}$ limit of 4000 K, the latter sample reaches much greater rotational periods and lower magnetic fields. The possible main reason for this is that R22 results are for field M dwarfs, while our work considers only M dwarf star members of the very young Pleiades open cluster. M dwarfs from the field may have had much more time to lose their magnetic fields and angular momentum when compared to the young stars from our sample.

The dependency between rotation and magnetic fields can be explained by the dynamo mechanism that converts kinetic into magnetic energy. The total magnetic field of the star is limited by its available kinetic energy, and this maximum magnetic field is described as $B_{\text{kin}}$. Here we adopt the relation from Reiners et al. (2009) for $B_{\text{kin}}$ (in units of Gauss):

$$B_{\text{kin}} = 4800 \times \left(\frac{ML^2}{R^7}\right)^{1/6}$$

(2)
where $L$ is the derived luminosity (in $L_\odot$ units), $M$ is the stellar mass (in $M_\odot$ units), and $R$ is the radius (in $R_\odot$ units) derived using the Stefan-Boltzmann equation, with the adopted $T_{\text{eff}}$. We derived magnetic fluxes ($\phi_B$) by multiplying the obtained average magnetic field by $4\pi R^2$. Masses were determined from isochrones, following the methodology discussed in Wanderley et al. (2023). In summary, we selected SPOTS isochrones from Somers et al. (2020) for 100 Myr and solar metallicity, interpolated isochrones associated with different photospheric spots fractions ($f_{\text{spots}}$), and adopted as the mass of the star the point in the interpolated isochrone plane with closest $T_{\text{eff}}$ and luminosity of the star.

We also estimated masses using DARTMOUTH (Dotter et al. 2008), MIST (Choi et al. 2016) and BHAC15 (Baraffe et al. 2015) isochrones, and found that, as expected, the choice of isochrone does not change significantly the $B_{\text{kin}}$ results.

Figure 5 presents our results for $<B>$ as a function of Rossby numbers (left panel), $<B>/B_{\text{kin}}$ (middle panel), and $\phi_B$ (right panel) as a function of rotational periods. Stars with $R_o>0.13$ are represented by open red circles, and stars with $R_o<0.13$ are represented by open blue circles. The grey dashed vertical line in the left panel at $R_o=0.13$ is the threshold that corresponds to the separation between the saturated and the non-saturated regimes.

For stars in the saturated regime in our sample (open blue circles), we derived relations between their mean magnetic fields with Rossby numbers, and between $<B>/B_{\text{kin}}$ and $\phi_B$ with rotational periods by using non-linear least squares to fit power-law functions. The obtained relations are found below and these are shown as solid blue lines in Figure 5.

\begin{equation}
< B > = 1604 G \times R_o^{-0.20} 
\end{equation}

\begin{equation}
< B > / B_{\text{kin}} = 1.13 \times P_{\text{rot}}^{-0.21} 
\end{equation}

\begin{equation}
\phi_B = 6.01 \times 10^{25} M x \times P_{\text{rot}}^{-0.23} 
\end{equation}

For comparison, we also show in Figure 5 similar relations derived by R22 for their sample of rapid and slow rotators (represented by cyan and red dashed lines, respectively).

As previously discussed in Figure 4, the results in the left panel of Figure 5 show a clear difference in the trends between the saturated and unsaturated regimes. The relation obtained here for the saturated stars (Equation 3)
is less steep than for the unsaturated ones and similar to the one derived in R22. Given the small number of slow-rotating stars and small range in Rossby number of our sample, we did not compute a best-fit relation for the unsaturated stars but the comparison of our results (open red circles) with the relation in R22 (red dashed line) shows good agreement. The results in the middle panel of Figure 5 show that overall most of our stars present <B>/>B<sub>kin</sub> ratios near 1 (represented by the grey horizontal dashed line), indicating that they are near the peak of magnetic energy production based on their available kinetic energy. There is a small trend with rotational periods (or Rossby numbers) showing an inverse correlation between <B>/B<sub>kin</sub> and rotational periods. This is illustrated by our derived relation for rapid rotators (Equation 4), which is very similar to the one derived by R22 (dashed blue line), presenting a similar slope, and being almost the same as our relation. The results in the right panel of Figure 5 show an overall similar behavior as found for <B>/B<sub>kin</sub> versus Rossby number, with saturated stars presenting a smaller dependency with P<sub>rot</sub> than non-saturated ones. This is illustrated by the blue solid line showing the relation between magnetic fluxes and rotational periods for the rapid rotator sample (Equation 5). The well-defined relation obtained here for the saturated regime for the Pleiades M dwarfs is different from the results in R22, who found a large scatter in magnetic fluxes for fast-rotating stars and without a well-defined relation. Such difference in the results may come from the fact that R22 studied field stars with different ages, while our sample has a well-constrained age of ~ 100 million years and, the well-defined trend for the saturated regime may be an indication of a strong connection between magnetic fluxes and stellar ages. The rotational periods and computed Rossby numbers, magnetic fluxes and <B>/B<sub>kin</sub> for the stars are presented in Table 2.

4.2. Radius Inflation in the Pleiades M dwarfs

Several works in the literature have compared stellar radii measurements with predicted radii from stellar isochrones that do not include magnetic fields and have found that stars, M dwarf stars in particular, have larger radii than predicted by the models (Reiners et al. 2012; Jackson et al. 2016, 2018, 2019; Jeffers et al. 2018; Kesseli et al. 2018; Jaechnig et al. 2019; Wanderley et al. 2023). Stellar magnetic fields can have the effect of decreasing convective efficiency and/or generating stellar spots, which reduces the stellar photospheric temperature and cause the star to inflate (Chabrier et al. 2007). The term radius inflation (R<sub>frac</sub>, fractional radius inflation) refers to the fractional difference between the radius obtained from measurements and isochrone models (R<sub>iso</sub>).

In this study, we follow the same methodology as discussed in Wanderley et al. (2023) to measure radius inflation for our sample of Pleiades M dwarfs, using as baseline MIST, DARTMOUTH, and BHAC15 isochrones with solar-metallicities and ages of 100 Myr. As discussed in Section 4.1, stellar radii were derived from the Stefan-Boltzmann equation, using adopted T<sub>eff</sub> along with luminosities derived from photometric relations. The median±MAD radius inflation obtained in this work is 7.0±1.5%, 6.5±1.4% and 5.4 ±1.3%, respectively, based upon the MIST, DARTMOUTH, and BHAC15 isochrones. A median radius inflation of ~5–7% found here for the Pleiades M dwarfs is considerably larger than the median radius inflation of ~2% that was obtained by Wanderley et al. (2023) for M-dwarf members of the older (age=625 ± 50 Myr, Perryman et al. 1998) Hyades open cluster. Greater radius inflation for younger M dwarfs, is generally in line with expectations from gyrochronology that stars from younger clusters should present higher average magnetic fields if compared to older stars with the same masses. It should be kept in mind, however, that while the sample of Wanderley et al. (2023) included M dwarfs beyond the fully convective threshold, our Pleiades sample is composed only of partially convective M dwarfs, and models including magnetic fields predict that radius inflation can be inhibited in fully convective stars (Feiden et al. 2015).

In addition, in this study, we also computed radius inflation using as a baseline SPOTS isochrone models from Somers et al. (2020). These models consider that stellar spots change the internal structure of the star by suppressing convection, reducing the photospheric temperature, and as a consequence inflating the star. As previously, to derive the fractional radius inflation (R<sub>frac</sub>) and photospheric spot fractions (f<sub>spots</sub>), we adopted SPOTS isochrones for solar metallicity, and an age of 100 Myr and the same methodology to measure radius inflation presented in Wanderley et al. (2023) (We refer to this previous study for details).

Using SPOTS models, we find a median radius inflation for our sample of 3.0±1.2%, which is smaller when compared to that obtained with either the MIST, DARTMOUTH or BHAC15 isochrones. Less radius inflation is expected when using Somers et al. (2020) isochrones as a baseline due to the decrease in luminosity for more spotted models. The median radius inflation found here for the Pleiades M dwarfs is larger than the median radius inflation of 1.0±0.5% reported by Wanderley et al. (2023) for the Hyades.
Figure 5. Comparison of different magnetic field indicators as a function of Rossby numbers (left panel) and rotational periods (middle and right panels). Stars with Ro<0.13 are represented by open blue circles, and stars with Ro>0.13 are represented by open red circles. The left panel presents the distribution of the obtained magnetic fields, the middle panel presents the ratio between the obtained average magnetic fields and the magnetic field limit based on the stellar kinetic energy and the right panel presents the magnetic flux of the stars. The left panel presents a vertical grey line to represent Ro=13. The horizontal grey line in the middle panel represents the point where the magnetic field is at its maximum physical limit, based on kinetic to magnetic energy conversion, where $B=B_{\text{kin}}$. We also show relations between rotational and magnetic parameters derived by this work (solid lines) and Reiners et al. (2022) (dashed lines), for slow (red lines) and/or rapid rotators (cyan lines).

Figure 6. Derived average magnetic fields and radius inflation for the sample 62 stars, considering different sets of isochrones. From left to right radius inflation is based on respectively MIST, DARTMOUTH, BHAC15, and SPOTS isochrones. The main result from all panels is that overall Pleiades M dwarfs having higher mean magnetic fields have more inflated radii. The work of Feiden et al. (2015) applied modifications in the DARTMOUTH models to include the effects of magnetic fields and found a positive correlation between magnetic field strength and radius inflation when considering either rotational or turbulent dynamos. This finding agrees with our results, as for all studied isochrones, stars with higher magnetic fields tend to be more inflated. However, a tendency for $B$ to have a weaker dependency with radius inflation, in particular for the SPOTS models with $R_{\text{rad}}$ between 0.02 and 0.10. Figure 7 presents the derived photospheric stellar spot fractions as a function of average magnetic fields. For the majority of the Pleiades M dwarfs, there is a positive correlation between stellar spot fractions and magnetic field, although with a small number of outliers. Finally, we note that there is one clear outlier star in Figures 6 and 7, having high radius inflation and low $B$. This star has the lowest $K_s$ mag from our sample ($K_s$ mag = 10.42; Skrutskie et al. (2006)). Its position the J-Ks vs Ks diagram (see Figure 1) might hint that it is not a member of the Pleiades cluster. However, this star was found in
Magnetic Fields of M Dwarfs from the Pleiades Open Cluster

Figure 7. Fractional stellar photospheric spots coverage from SPOTS models (Somers et al. 2020), as a function of our derived average magnetic fields.

Cantat-Gaudin et al. (2020) to have a 100% probability of being a member of the Pleiades. Note that our \( f_{\text{spots}} \) may progressively increase for \( <B> \) larger than roughly 2500 G. Although, Cao & Pinsonneault (2022) previously found constant \( f_{\text{spots}} \) at low Rossby number (\( \text{Ro} < 0.21 \)) in their analysis of Pleiades dwarfs with their values of \( f_{\text{spots}} \) modeled from a two-component surface defined by a star-spot filling factor and a star-spot temperature contrast.

4.3. Magnetic Fields and Activity

Stellar activity is a term that represents the stellar variability phenomenon which is mainly a consequence of strong magnetic fields. Stellar variability can be caused by stellar spots, which are temporary cooler regions in the stellar photosphere where the strong magnetic fields suppress convection. As the star rotates these cold spots can reduce the observed stellar flux, and result in periodic changes in the magnitude of the star. Another important mechanism that can generate stellar variability is high-energy non-thermal emission. Strong magnetic fields are responsible for heating the coronae and chromosphere of active stars, which results in considerably larger amounts of high-energy radiation emission than expected from their black-body profiles. Heating of the coronae results in excess in the X-ray stellar output that can be measured as the ratio between the X-ray and bolometric luminosity ratios versus our derived magnetic fields. There is a clear correlation between the two variables, with a Pearson correlation coefficient of 0.46 for the sample in Núñez & Agüeros (2016) (shown as maroon circles) and 0.35 for the sample in Wright et al. (2011) (shown as orange circles), indicating that stars with stronger magnetic fields tend to present greater X-ray to bolometric luminosity ratios.

Concerning chromospheric activity the work of Fang et al. (2018) measured equivalent widths for \( \text{H}_\alpha \), \( \text{H}_\beta \), and \( \text{Ca II} \) K emission lines for stars in open clusters using LAMOST DR3 spectra (Cui et al. 2012). We cross-matched our Pleiades sample with their database and found 33 stars in common with measured \( \text{H}_\alpha \), 31 with measured \( \text{H}_\beta \), and 19 with measured \( \text{Ca II} \) K. The three fields, they are also variable, and change according to the stellar magnetic cycle.

To study the relation between activity and magnetic fields in the Pleiades M dwarfs, we cross-matched our sample with the targets in the X-ray studies by Núñez & Agüeros (2016) and Wright et al. (2011), and found 31 stars in common with the first study (not considering 17 stars having only upper limit measurements), and 19 stars in common with the latter study; the X-ray to bolometric luminosity ratios in those works are X-ray flux measurements from Einstein and ROSAT observations (Micela et al. 1990; Stauffer et al. 1994; Micela et al. 1996, 1999; Stelzer et al. 2000). The results are summarized in the top panel of Figure 8 where we show the logarithm of the X-ray to bolometric luminosity ratios versus our derived magnetic fields. There is a clear correlation between the two variables, with a Pearson correlation coefficient of 0.46 for the sample in Núñez & Agüeros (2016) (shown as maroon circles) and 0.35 for the sample in Wright et al. (2011) (shown as orange circles), indicating that stars with stronger magnetic fields tend to present greater X-ray to bolometric luminosity ratios.
panels in Figure 9 present our derived average magnetic field measurements versus the total equivalent width for the Ca II K line (top panel), Hβ (middle panel), and Hα (bottom panel), all equivalent widths are in units of Å. Similarly to what was found for the X-ray to bolometric ratios, there is a correlation between the mean magnetic fields for the Pleiades M dwarfs and the equivalent widths of the emission lines for all three lines, although the results for the Ca II K line are less clear.

Figure 10 shows the Hα to bolometric luminosity ratios as a function of mean magnetic field for stars in our sample having Hα emission strength measurements (EW\textsubscript{Hα}) reported in Table 2. To convert Hα equivalent widths into L\textsubscript{Hα}/L\textsubscript{bol} we employed the methodology described in Stassun et al. (2012). Similarly to what is seen for the relation between EW\textsubscript{Hα} and <B> (bottom panel of Figure 9), there is a clear correlation between Hα to bolometric luminosity ratios and the derived magnetic fields, with a Pearson correlation coefficient of 0.78.

Overall, it is reassuring that in this study we find that the more magnetic stars in our sample tend also to be more active, and this is based on our magnetic field measurements and independent results from activity indicators from other works in the literature. The X-ray and Hα to bolometric luminosity ratios as well as the equivalent widths for Hα, Hβ and Ca II K of the stars are presented in Table 2.

5. CONCLUSIONS

We used the SYNMAST code Kochukhov et al. (2010), along with a Markov Chain Monte Carlo (MCMC) methodology, to compute synthetic spectra and analyze magnetically sensitive Fe I lines to derive average magnetic fields for 62 M dwarf members of the young (age = 112 ± 5 Myr; Dahm 2015) and nearby Pleiades open cluster. This analysis is based on the SDSS IV APOGEE spectra (Majewski et al. 2017; Abdurro’uf et al. 2022), the APOGEE line list (Smith et al. 2021), effective Landé-g factors from VALD (Piskunov et al. 1995; Kupka et al. 1999), and model atmospheres from the MARCS grid (Gustafsson et al. 2008).

A search was carried out to find the best Fe I lines in the APOGEE spectral region that were sensitive to Zeeman broadening and could be used as diagnostic lines for measuring mean magnetic fields in M dwarfs, with four Fe I lines identified and selected as the best indicators: λ15207.526 Å, λ15294.56 Å, λ15621.654 Å, and λ15631.948 Å. The derived mean magnetic fields for the studied Pleiades M dwarf stars range from ∼1.0 to ∼4.2 kG, with a median±MAD of 3.0±0.3 kG, not reaching the lowest magnetic field and rotation levels reported in other studies that explored field stars of similar masses, which is probably explained by the young age of the cluster.

The derived mean magnetic field measurements in the Pleiades M dwarfs were used to study correlations with Rossby number (Ro) and stellar rotation. The Rossby number

**Figure 9.** Derived average magnetic fields as a function of equivalent widths of magnetic sensitive chromospheric emission lines for stars of our sample that are in common with the work of Fang et al. (2018). The panels present from top to bottom: Ca II K, Hβ and Hα emission lines.

**Figure 10.** Derived average magnetic fields as a function of Hα to bolometric luminosities. We employed the methodology described in Stassun et al. (2012) to convert Hα equivalent widths (taken from Fang et al. (2018)) into L\textsubscript{Hα}/L\textsubscript{bol}.
number is given by the ratio between the rotational period and the convective turnover time, being an important indicator of stellar activity. We find a clear trend that more magnetic stars have, on average, higher projected rotational velocities, $v\sin i$. The Rossby number was used to separate our sample into rapid ($\text{Ro}<0.13$) and slow rotators ($\text{Ro}>0.13$). Overall, our results for $<B>$ versus $P_{\text{rot}}$ and $B$ versus Rossby number overlap with results from the literature for field stars, and indicate that the population of stars with $\text{Ro}<0.13$ exhibit a steeper relation between magnetic field and rotational period, or Rossby number, when compared to stars with $\text{Ro}>0.13$. However, even for $\text{Ro}>0.13$, there remains a shallow trend between Rossby number and magnetic field, which is given by: $<B> = 1604 \times \text{Ro}^{-0.20}$.

For this sample of Pleiades M dwarfs, we also investigated the ratio between mean magnetic fields and the maximum magnetic field limit ($<B>/B_{\text{kin}}$) that is reached based on the kinetic-to-magnetic energy conversion. It is found that most of the studied Pleiades M dwarfs are at the limit of kinetic to magnetic energy conversion, or, are in the saturated regime, having $<B>/B_{\text{kin}} \approx 1$. Unlike previous results in the literature for field stars in the saturated regime, the computed stellar magnetic fluxes $\Phi_B$ as a function of Prot for the Pleiades M dwarfs show similar trends obtained for $<B>$ versus Prot.

Another important effect of magnetic fields is to inflate the stellar radii of cool dwarfs. Radius inflation corresponds to the fractional difference ($R_{\text{frac}}$) between the radius obtained from measurements and predictions from isochrone models. In this study, we derived the radii for the studied M dwarfs and used MIST, DARTMOUTH, BHAC15, and SPOTS isochrones as baselines to infer their radius inflation. We obtain a median±MAD radius inflation for our sample of respectively $7.0 \pm 1.5\%$, $6.5 \pm 1.4\%$, $5.4 \pm 1.3\%$ and $3.0 \pm 1.2\%$, being more inflated than M dwarfs in the older Hyades open cluster Wanderley et al. (2023). For the Pleiades, it is noticeable that for SPOTS isochrones there is less radius inflation when compared to non-spotted isochrones, as expected. In addition, our results indicate that more magnetic stars have more inflated radii, showing a correlation between $R_{\text{frac}}$ and $<B>$. For SPOTS models in particular, there is, however, a tendency for $<B>$ to exhibit a weaker dependency with radius inflation for $R_{\text{frac}}$ between 0.02 and 0.10. For the majority of the Pleiades M dwarfs in our sample, there is a positive correlation between stellar spot fraction and magnetic field, although with a small number of outliers.

To study the relation between chromospheric stellar activity and magnetic fields in the Pleiades M dwarfs, we compared our derived mean magnetic fields with high-energy non-thermal emission indicators, such as equivalent width measurements of the lines of Hα, Hβ, and Ca II K, as well as Hα to bolometric luminosity ratios. For all of these, we find a positive correlation between chromospheric activity and magnetic fields. A positive correlation was also obtained between the mean magnetic field and the ratio between X-ray to bolometric luminosity, which is an important indicator of coronal activity. Overall, it is reassuring that the more magnetic stars in this study also tend to be more active, and this is based on our magnetic field measurements from APOGEE spectra, which is independent of the results for activity indicators obtained from the literature. This study opens a new window into using the APOGEE survey to investigate magnetic fields in cool stars.

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Table 1. Filling Factors

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Table 2. Stellar Data

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The complete Table is available in electronic format.

$^{a}$Wright et al. (2011)

$^{b}$Núñez & Agüeros (2016)

Table 3. Diagnostic lines

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<th>$\chi_{\text{exc}}$</th>
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REFERENCES


Han, E., López-Valdèria, R., Mace, G. N., & Jaffe, D. T. 2023, AJ, 166, 4
Hubeny, I., & Lanz, T. 2011, Synspec: General Spectrum Synthesis Program, Astrophysics Source Code Library, record ascl:1109.022
Hunter, J. D. 2007, Computing in Science & Engineering, 9, 90
Kesseli, A. Y., Muirhead, P. S., Mann, A. W., & Mace, G. 2018, AJ, 155, 225
—. 2021, A&A Rv, 29, 1


