Red Dwarf Stars: Ages, Rotation, Magnetic Dynamo Activity and the Habitability of Hosted Planets

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Abstract. We report on our continued efforts to understand and delineate the magnetic dynamo-induced behavior/variability of red dwarf (K5 V – M6 V) stars over their long lifetimes. These properties include: rotation, light variations (from star spots), coronal–chromospheric XUV activity and flares. This study is being carried out as part of the NSF-sponsored Living with a Red Dwarf program¹. The Living with a Red Dwarf program’s database of dM stars with photometrically determined rotation rates (from starspot modulations) continues to expand, as does the inventory of archival XUV observations. Recently, the photometric properties of several hundred dM stars from the Kepler database are being analyzed to determine the rotation rates, starspot areal coverage/distributions and stellar flare rates. When all data sets are combined with ages from cluster/population memberships and kinematics, the determination of Age-Rotation-Activity relationships is possible. Such relationships have broad impacts not only on the studies of magnetic dynamo theory and angular momentum loss of low-mass stars with deep convective zones, but also on the suitability of planets hosted by red dwarfs to support life. With intrinsically low luminosities ($L < 0.02L_\odot$), the liquid water habitable zones (HZs) for hosted planets are very close to their host stars – typically at $\sim 0.1 \text{ AU} < \text{HZ} < 0.4 \text{ AU}$. Planets located close to their host stars risk damage and atmospheric loss from coronal & chromospheric XUV radiation, flares and plasma blasts via strong winds and coronal mass ejections. In addition, our relationships permit the stellar ages to be determined through measures of either the stars’ rotation periods (best way) or XUV activity levels. This also permits a determination of the ages of their hosted planets. We illustrate this with examples of age determinations of the exoplanet systems: GJ 581 and HD 85512 (both with large Earth-size planets within the host star’s HZ), GJ 1214 (hot, close-in transiting super-Earth planet) and HD 189733 (short period, hot-Jupiter planet interacting with its host star – age from its dM4 star companion).

1. Background & Introduction

Studying red dwarf stars (K5 V – M6 V – “K/M stars” hereafter) is important because they are the most populous stars in the Galaxy (>80% of all stars – see Fig. 1a) and could be hosts to numerous planets, some of which may be suitable for life. Even though the vast majority of stars being searched for planets are brighter F, G and early K stars, thus far > 30 exoplanets have been found orbiting red dwarfs, many of which are super-Earths ($\sim 2-10 M_\oplus$) – Mayor et al. (2009); Engle et al. (2009). One of the primary motivations for the Living with a Red Dwarf program is to investigate

¹The Program website can be found at http://astronomy.villanova.edu/LWARD
Figure 1. **Left – (a)** – Inventory of known stars within 10-pc, binned by spectral type. Note: dM stars represent >75% of the main-sequence stars. **Right – (b)** – Luminosity changes over time for representative F5 V, G2 V, K2 V and M1–2 V stars. The evolution tracks are from BaSTI (http://albione.oa-teramo.inaf.it/). Note: the luminosities of the lower mass dK and dM stars change very slowly with time.

whether these numerous, cool, low mass, low luminosity stars with extremely long (Fig. 1b) main-sequence lifetimes (>100 Gyr) are suitable for life on hosted planets in their close-in liquid water habitable zones (“HZs” < 0.4 AU). We cannot realistically extrapolate our solar-type results to K/M stars since they are fundamentally different (mass/luminosity) and have deep convective zones (CZs – fully convective atmospheres cooler than ∼dM3.5). Though the specific origin of magnetic activity in red dwarf stars is still debated, they are theorized to operate under the $\alpha^2$ (turbulent) dynamo, as opposed to the $\alpha-\omega$ (shear interface) dynamo of the Sun and other solar-type stars. In theory, the $\alpha^2$ dynamo is driven purely by convective motion, where the $\alpha-\omega$ dynamo relies on convection and differential rotation. Previous X-ray studies show red dwarf stars have very “efficient” dynamos, with $L_X/L_{bol}$ values and chromospheric UV surface fluxes up to $\sim100\times$ those of comparable age (or rotation) solar type stars.

### 2. The Living with a Red Dwarf Program

We have extended our ongoing *Sun in Time* program (Guinan et al. 2003; Guinan & Engle 2009) on solar dynamo physics, angular momentum loss, Age-Rotation-Activity relations & XUV (X-ray – UV; ∼10–3200Å) irradiances (and effects on planetary atmospheres and life) of solar type stars to more numerous, cooler red dwarfs. With the support of the U.S. National Science Foundation (NSF), we have been carrying out a comprehensive study of main sequence K/M stars across the electromagnetic spectrum. This *Living with a Red Dwarf* program includes ∼400+ nearby dK/M stars with a wide range of ages (∼0.1–12 Gyr) and rotations ($P_{\text{rot}} \approx 0.4–190\text{-d}$) that have vastly different levels of age/rotation dependent chromospheric UV, Ca $\text{n HK}$ and H$\alpha$ emissions, as well as corresponding transition region (TR) FUV–UV and coronal X-ray emissions. So far, from ground based photometry, we have determined rotation periods (from star spot brightness modulations), star spot fill-factors and flare frequencies for ∼140 of these stars (Engle et al. 2009). Sample light curves are shown in Fig. 2.

In addition, we are utilizing the HEASARC X-ray (*ROSAT, XMM* and *Chandra*) and MAST FUV–UV (*IUE, HST* and *FUSE*) archives to determine the XUV fluxes for a subset of the program stars. To fill in gaps in coronal X-ray coverage, we are currently
observing a sample of dM stars (with reliable ages) with the Chandra X-ray Observatory. As in the Sun in Time program, we are developing X-ray–UV irradiance measures for red dwarf stars. Our study (and others) shows that young red dwarf stars rotate rapidly and subsequently lose angular momentum over time, slowing their rotation and consequently weakening their magnetic dynamos, resulting in significantly diminished coronal X-ray and chromospheric UV emissions with stellar age. There is also evidence for a “funneling effect” in G/K/M stars, where stars >1 Gyr in age show a tighter correlation between age and rotation as compared to stars <1 Gyr, which display a good bit of scatter. The compensation mechanism is such: if you take two ZAMS K/M stars – and Star A is rotating much more rapidly than Star B – then Star A will have a more robust dynamo with stronger winds, and will lose angular momentum (and spin-down) more rapidly than Star B. This mechanism will bring the two stars to a similar rotation rate as they age.

3. Age-Rotation-Activity Relationships for dM Stars

3.1. Photometrically Determined Rotation Periods for dM stars

We have been carrying out photometry (or utilizing archival photometry) of a representative sample of ~400 K/M stars to determine rotation periods, starspot and flare properties. As found in this study, the rotation periods of K/M stars are indicative of their ages (see Fig. 3a). In fact, rotation rates are a more direct indicator of age than activity measures like Ca ii, H$_\alpha$ or L$_X$, because these measures can be affected by: rotation effects (starspots/plages), activity cycles & flaring. But the spin-down is dependent on spectral type (mass and convective zone (CZ) depth). However, in very young populations (ages < 0.5 Gyr), the rotation periods of red dwarfs typically range from <0.5-days up to ~10 days (most less than 5-days) for the same age bracket – e.g. Messina et al. (2010). This arises from differing initial conditions and the inclusion of
pre-main sequence stars and close binaries in the sample. Also in this study, we exclude spectral types later than ~M7 because they appear to have Age-Rotation-Activity relations quite different to earlier spectral types. From a limited sample of M7–9 V stars, it appears that they do not undergo magnetic breaking over time.

Young K/M stars typically spin rapidly and have correspondingly robust dynamos & magnetic activity. Over time, though, they lose angular momentum via magnetized stellar winds and their rotation periods lengthen and their (magnetic-induced) activity decreases. This is illustrated in Fig. 3a showing the $P_{\text{rot}}$-Age relation for program dM0–5 stars, and Fig. 3b shows the (coronal X-ray) $\log L_X$-Age relation. Photometry is being conducted using the 0.8-m Four College Automatic Photoelectric Telescope (FCAPT) and the 1.3-m Robotically Controlled Telescope (RCT), both located in Arizona. This study has uncovered low amplitude rotational light modulations (and thus rotation periods) for many of these stars. There is also compelling evidence of long-term light and activity variations in some of these stars (e.g. Proxima Cen – $P_{\text{cyc}} \approx 7.1$-yr – from both light and X-ray variations) indicative of solar-like magnetic activity cycles. We have also been searching for light variations in additional equatorial and southern K/M stars included in the All Sky Automated Survey (ASAS-3; Pojmanski (2001)). Utilizing the period search routines in the latest version of the Period Analysis Software (Peranso – http://www.peranso.com), strong evidence of periodicity and long-term systematic variations in brightness have been uncovered for dozens of additional K/M stars, including Proxima Cen. To broaden the database, we have recently been utilizing ultra-high precision, time series photometry of ~1000+ K/M stars from the Kepler Mission to determine precise rotation periods and unprecedented information on starspot genesis and evolution, as well as new information on flaring frequencies of red dwarfs. These results will be discussed in an upcoming report.

3.2. Age by Association: Determining the Ages of K/M Stars

It is crucial for this study that we have reliable age estimates to study the evolution of angular momentum, magnetic activity & XUV spectral irradiance. However, securing reliable ages of field K/M stars is next to impossible for red dwarf stars because of their extremely slow nuclear evolution. Once reaching the ZAMS, the stars’ measureable properties – such as $M_V$, $T_{\text{eff}}$, $\log g$ are essentially constant over time scales of the tens of billions of years (Fig. 1b). The essentially fixed luminosities of K/M stars (and thus fixed HZs) could be favorable for the formation and evolution of life on possible hosted HZ planets. But this is an obvious drawback for determining ages of red dwarfs from isochronal fits (in $L$–$T_{\text{eff}}$ space). For example, over the ~4.6 Gyr lifetime of the Sun, its luminosity has increased by ~30%. By contrast, a mid-dM star would undergo a luminosity increase of <1% over the same time period. Until recently, the ages of K/M stars could only be reliably determined from memberships in nearby star clusters or moving groups with reliable ages (almost entirely < 2 Gyr), or statistically inferred from sufficiently high $UVW$ space motions, indicating either Old Disk (~7–10 Gyr) or Halo (~10–13 Gyr) ages. For example, ages for young (200–650 Myr) K/M stars can be found from memberships in nearby open clusters such as the Castor moving group (~200 Myr), the Ursa Major (UMa) moving group (~300–550 Myr), the Hyades cluster (~625 Myr) and the HR 1614 moving group (~2 Gyr). The Rotation-Age and $\log L_X$-Age relations (for M0 V – M5 V stars only) are shown in Figure 3.

A recent, important “age method” for red dwarfs is membership in wide binaries and common proper motion pairs where the companion star’s age is known from
Figure 3. **Left – (a)** – The photometrically determined rotation rates of dM stars are plotted vs. age. The data thus far indicates a linear trend, in surprising contrast to what has been found for dG and dK stars. **Right – (b)** – The decrease in coronal X-ray emission (log $L_X$) of dM stars is shown. Saturation occurs at age < 0.3 Gyr.

3.3. Examples of Age-Rotation-Activity Relation Calibration and Applications

Here we present several example applications of our Age-Rotation-Activity relations, and discuss the calibration of these relations with the 40 Eri ABC and G 111-72 systems. Both of these star systems have WD components with reliable ages. We also illustrate the age determinations of two (the only two so far) exoplanet systems (GJ 581 and HD 85512) that host super-Earths orbiting within the host K/M star’s HZ, and discuss a new result for the short-period transiting Hot Jupiter around HD 189733, whose true age and dynamic nature are inferred from the age determination of a recently identified faint M4–5 V companion. We also discuss the age determination for GJ 1214 – a newly discovered transiting, short-period, hot super-Earth planet system.

**Applying WD evolution+cooling time ages to the 40 Eri & G 111-72 systems:**

40 Eri ABC is a nearby (16.5 ly) triple star system that consists of a 4.4-mag K1 V star, a 9.5-mag DA4 white dwarf and a 11.2-mag M4.5 V star. The WD component, 40 Eri B, has well-determined physical properties ($T_{\text{eff}}, M/M_\odot, L/L_\odot$ and $\log g$) that permit its age to be reliably calculated from the WD cooling time and progenitor evolu-
tionary age. Two recent independent age determinations for the 40 Eri B are essentially identical, yielding an age of 5.1±0.7 Gyr (Ballouz et al. 2010; Zhao et al. 2011). We used this WD age to calibrate the measured Ca ii HK and coronal X-ray luminosity (Lx) of the K1 V and M4.5 V stars. We have been carrying out photometry to determine the photometric rotation periods for these benchmark stars.

We have also been carrying out photometry and spectroscopy of wide binary WD + K/M system that have good WD age estimates. So far this has resulted in rotation periods for the dM-star components of several WD+dM wide pairs with ages. For example, G 111-72 (age ≈ 2.5 Gyr) has been found to have a photometric rotation period of \( P_{\text{rot}} = 39.86 \) days. These stars are plotted in Fig. 3). Several of these stars also have been approved for X-ray observations by Chandra during 2011/12.

**Ages of super-Earth Planets Hosted by Red Dwarfs – Examples:**

**GJ 581:** The nearby M3 V red dwarf GJ 581 (distance ≈ 20 ly) is one of the most famous host stars of potentially habitable planets. At present, GJ 581 is the nearest star system with super-Earth planets that could be suitable for life. The exact number of super-Earth type planets hosted by GJ 581 is still debated – the most recent HARPS radial velocity study indicates the presence of four exoplanets (Forveille et al. 2011) instead of the six planets previously reported by Vogt et al. (2010). Noteworthy, two of the large Earth-mass planets, GJ 581c \( (P = 12.92; a = 0.07 \; \text{AU}; \; M \sin i = 5.32 \; M_{\oplus}) \) and GJ 581d \( (P = 66.6; a = 0.22 \; \text{AU}; \; M \sin i = 6.1 \; M_{\oplus}) \) remain of great interest because they are located close to the inner (hot) edge and outer (cold) edge of the M3 V star’s habitable zone (Fig. 5a). Depending on the atmospheric properties of the planets (atmospheric composition/circulation, density and albedos) these planets could have conditions favorable for the development of life (Fig. 5b). Habitability also depends on the age and activity of the host star. From our rotation-age relation, we estimate an age = 5.7±0.8 Gyr from the \( P_{\text{rot}} = 93.2 \) days reported by Vogt et al. (2010). This age estimate is in excellent agreement with that of 4–8 Gyr indicated from the star’s \( L_x \) upper limit of \( \log L_x < 26.4 \) ergs/s and Ca ii HK emissions.

**HD 85512:** Recently, a large Earth-size planet has been found orbiting the nearby K5 V star HD 85512 (Pepe et al. 2011). This is important since, like GJ 581c, HD 85512b orbits near the inner edge of the star’s HZ and could have conditions suitable for life (Kaltenegger et al. 2011). HD 85512 has a slow rotation period (for mid-dK stars) of 47.1±7 days (Pepe et al. 2011). This period, if correct, indicates an age of 8±2.5 Gyr.
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(from our $P_{\text{rot}}$-Age relation for early/mid-dK stars (Wolfe et al. 2010); somewhat older than the Ca II HK ($R'_{\text{HK}}$) age estimate of 5.6±0.6 Gyr by Pepe et al. (2011)).

**GJ 1214:** Another system to which our method has been applied is that of GJ 1214 – a dM4 star with a transiting, hot super-Earth. The planet has a mass of 6.45 M$_{\oplus}$, an orbital period of 1.58-days and an estimated equilibrium temperature of $\sim$500 K (Berta et al. 2011). Utilizing photometry from the MEarth Program, Berta et al. found a likely stellar rotation period of $\sim$53-days. Applying our $P_{\text{rot}}$–Age relation, we find age = 3.2±0.6 Gyr, which agrees with the >3 Gyr lower age limit of Berta et al. (2011).

**Evidence of Host Star Spin-Up by Close-In Hot Jupiters: the Case of HD 189733:**

Our recent study of the bright, short period transiting exoplanet system HD 189733 provides an excellent example of what new information can be found once the age of the star is determined (Santapaga et al. 2011). HD 189733 A is a K2 V star that has attracted much attention because it hosts a transiting, hot Jupiter-exoplanet. HD189733b has one of the shortest known orbital-periods ($P$ = 2.22-days) and is only 0.031 AU from its host star (Bouchy et al. 2005). HD 189733 A has a $P_{\text{rot}}$ = 12-d, coronal $L_X \approx 10^{28}$ ergs/s, and moderate-to-strong chromospheric Ca II-HK emission, all indicating an age $\approx$ 0.6–1.0 Gyr (as inferred from our Age-Rotation-Activity relations for early dK stars. However, this age is discrepant with an older-age inferred from the star’s low Lithium-abundance ($\frac{1}{10}$ Solar). But the Age-Rotation-Activity determination assumes no tidal effects from companions – such as a close planet. Bakos et al. (2006) discovered a dM4 companion star (HD 189733 B: 12” distance to the K2 V star). XMM – Newton observations of HD 189733 A&B carried out recently by Pillitteri et al. (2010), surprisingly revealed that HD 189733 B shows no X-ray emission, with an upper limit of $L_X < 9 \times 10^{26}$ ergs/s. Our $L_X$-Age relationship (Fig. 3b) indicates an age for the dM4 star of $> 4$ Gyr. Also the lack of H$\alpha$ emission and weak Ca II HK emission in the dM star’s spectra indicate weak magnetic activity consistent with slow rotation and a lower limit age of $\sim$4 Gyr. These age proxies indicate that the binary is indeed old and that the fast rotation and corresponding high levels of activity for the K2 V star can be resolved if this star has been spun-up by its nearby planetary companion. Thus, the planet’s orbital angular momentum has been transferred to HD 189733 A via tidal and/or magnetic interactions. Cohen et al. (2011) have recently discussed evidence for magnetic interactions between the planet and the host star as well as the probable effects of tidal and magnetic interactions. This loss of orbital angular momentum by the planet should eventually cause the planet to spiral inward and be disrupted near its Roche lobe.

### 3.4. Constructing K/M Star X-ray–UV (XUV) Irradiances

A detailed characterization of K/M star radiation, plasma environments and changes with time is very important to the study of extrasolar planets – especially for Earth-size HZ planets with potential for life. Because of their slow nuclear evolution rates, the luminosity and $T_{\text{eff}}$ of the stars and resulting photospheric spectral radiances (from ~3000Å out to IR wavelengths) remain essentially fixed with time for a given mass. However, the radiation at shorter wavelengths (the XUV region) arises from dynamo-generated coronal, TR and chromospheric emissions, and undergoes a measurable decrease as the stars lose angular momentum with age (Fig.6a). XUV radiation can profoundly affect planetary atmospheres, due to photoionization and photochemical reactions, along with ion pickup processes from stellar winds impacting planetary thermospheres (Lammer et al. 2003; Grießmeier et al. 2004; Ribas et al. 2005; Tian 2009).
Figure 5. **Left – (a)** – Illustration of the GJ 581 planetary system, plotting the orbits of GJ 581b, c, and d. Super-Earths “c” and “d” are located near the inner (warm) and outer (cold) edges of the star’s habitable zone. **Right – (b)** – Illustration of planet GJ 581c showing the synchronization of its ~13-d orbital and rotation periods. The thermal effects of a thin (<0.1 Bar) and thick (1 Bar) atmosphere are shown. In the thick atmosphere case, the dark hemisphere of GJ 581c could have temperatures suitable to support life via atmospheric circulation. With a strong greenhouse effect, planet GJ 581d could also be suitable for life on its starlit side.

The XUV irradiance tables (~10–3200Å) we are developing will be important for studying the evolution of the atmospheres of planets hosted by K/M stars. The FUV/NUV irradiances of representative G, K, and M stars are shown in Fig. 6b. In particular, the age sequence of spectral irradiances from our sample (e.g. Fig. 3b for coronal X-rays and Fig. 6a for FUV variations with age) can delineate not only the present state of the new extrasolar planets detected, but also the evolution of their atmospheres and can assess the possibility of life. One major effect that XUV radiation can have (in combination with stellar wind interactions) is the erosion of the host planet’s atmosphere (Lammer et al. 2003; Grießmeier et al. 2004). As discussed by Grießmeier et al. (2004), close-in planets without strong (protective) magnetic fields are especially susceptible to atmospheric erosion & loss by the star’s XUV and wind (plasma) fluxes. Also, the frequent flaring of dM stars (especially those with ages < 1 Gyr) and tidal locking of close-in planets could challenge the development of life. If life were to form, however, the long lifetimes of the host K/M star could be favorable to the development of complex (possibly even intelligent) life. Numerous dM stars in the solar neighborhood are old (> 5 Gyr), presenting possibilities for highly advanced forms of intelligent life (Tarter et al. 2007). Additionally, young red dwarf stars undergo frequent flares, in which their UV fluxes increase 10–100× for several minutes. The increased XUV flare radiation could have further adverse effects on the retention of a planet’s atmosphere and be harmful to possible life on its surface. Recently, however, Tian (2009) evaluated the ability of a 6–10 M⊕ super-Earth to retain a primary CO₂ atmosphere while orbiting a dM star. Tian found that the atmosphere could be retained, even for dM star XUV activity up to 1000× that of the Sun.

**4. Conclusions & Future Prospects**

The *Living with a Red Dwarf* program, when completed, should provide valuable data for the study of exoplanets by providing the age estimates, magnetic evolution and re-
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Figure 6. **Left – (a)** – The FUV (1250–1850Å) spectrophotometric fluxes (adjusted for distance) of three dM stars of different ages are shown. The chromospheric and TR line emissions decrease significantly (down to $\sim 1/100$ the original level) over an age range of 0.2–5.8 Gyr. **Right – (b)** – The FUV (1200–2000Å) and NUV (2000–3200Å) irradiance plots computed for the respective habitable zones for young G, K and M stars are shown. In the FUV, line emissions dominate and are nearly equal for these stars. But in the NUV, photospheric continuum flux dominates for the G1 V and K2 V stars; for the red dwarf there is essentially no NUV radiation outside of flares.

As a result, XUV emissions of their host stars. The Age-Rotation-Activity relationships for red dwarf stars found through this program will allow galactic red dwarfs to have reliably determined ages based on photometric rotation periods or measures of X-ray, Ca II HK ($R_{\text{HK}}'$) or Hα emissions (and accurate spectral type for best precision). This could be especially important in realizing ages (from rotation) for the thousands of red dwarfs being observed by Kepler. In addition, as part of the Sloan Digital Sky Survey program, about 50,000 spectra of K/M stars have been secured (Bochanski et al. 2011). We are also developing Hα-Age emission relations for program stars with Stella Kafka (Carnegie Inst., DTM). From results in hand, there are good (but preliminary) correlations between Hα emission and age for subsets of dM star, in which Hα emission decreases with age. Surprisingly, our program K/M stars, although smaller with deeper CZs and possibly even different dynamo mechanisms, behave/evolve in a similar manner (but achieving much longer rotation periods) to solar-type stars. When this study is realized, it may be possible to estimate approximate ages of the numerous SDSS red dwarfs that have spectra – an important tool for galactic structure studies. With the ages of red dwarf star planetary systems reliably known, the dynamic evolutionary history and stability of the system can then be assessed. Furthermore, the past, present and future XUV radiative environments that the planets will face can be estimated. Also under study is the characterization of frequent flares that red dwarf stars display, in which their UV fluxes increase 10–100× for several minutes. The increased XUV radiation from flares could have adverse effects on the retention of a planet’s atmosphere and be harmful to possible life on its surface. Finally, planetary habitability can be assessed based on the irradiance data and statistical possibilities can be assigned to whether or not life could originate and evolve on a planet hosted by a red dwarf.

Thus, potentially habitable planets around red dwarfs are clearly an important issue for future study. Dedicated search programs for planets orbiting K/M stars are being developed. For example, the Carnegie Planet Finder Spectrograph (PFS – < 1 m/s precision optical echelle) is now in use on the 6.5-m Magellan II telescope, and is
emphasizing K/M stars as its primary targets. Also, the High Accuracy Radial velocity Planet Searcher (HARPS) instrument at La Silla achieves a similar precision, has been operating since 2003 and has made numerous discoveries concerning both planets and various aspects of stellar activity. Another ground-based program is the the MEarth project - a transit survey of ~2000 dM stars in the northern hemisphere (Irwin et al. 2009). MEarth can detect transits by bodies as small as ~2 $R_{\oplus}$. Also, space-based planet search missions, including CoRoT, Kepler and, in the future, Plato and (maybe) Darwin/TPF, are planning to target many additional red dwarf stars. It now appears timely to assess the likelihood of life not only around main sequence dG & dK stars, like our Sun, but also around the very numerous, low luminosity dM stars.

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