The “Living with a Red Dwarf” Program

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Abstract. Red Dwarfs (main-sequence / dwarf M or dM) stars are the most common stars in the Galaxy. These cool, faint, low mass stars comprise over 75\% of all stars. Because of their low luminosities (\sim 0.0008–0.06 of the Sun’s luminosity), the circumstellar habitable zones (HZs) of dM stars are located within \sim 0.05–0.4 AU of the host star. Nevertheless, the prospect of life on a planet located within the HZ of a red dwarf is moderately high, based on the longevity of these stars (>50 Gyr), their constant luminosities and high space densities. Here we describe the aims and early results of the “Living with a Red Dwarf” Program – a study of dM stars that we have been carrying out over the last few years. The primary focus of our research on dM stars is the study of their magnetic dynamos and resulting star spots & coronal X-ray and chromospheric UV emissions as a function of age, rotation and spectral type. This program will provide datasets that can be used as inputs for the study of all aspects of dM stars, along with the planets already discovered hosted by them and the probable hundreds (thousands?) of planets expected to be uncovered in the near future by missions such as Kepler & Darwin/TPF. These datasets will be invaluable to those who model exo-planetary atmospheres, as well as exobiologists & astrobiologists who are studying the possibilities of life elsewhere in the universe. Our expected results will provide fundamental information on the most numerous stars in the Galaxy – including their ages, as well as radiative (irradiances) and magnetic dynamo properties. A significant element of our program is the determination of accurate stellar magnetic-driven X-ray–UV (X-UV) irradiances that are generated by the dM stars’ vigorous magnetic dynamos. These X-UV irradiances (and flare frequencies) are strongly dependent on rotation, and thus age, and diminish as the stars lose angular momentum and spin-down over time via magnetic braking.

1. Background & Introduction

Red dwarf stars (also known as main-sequence M or dwarf M – dM stars) are by far the most numerous stars in our Galaxy, comprising more than 75\% of all stars (see Fig. 1a). dM stars are cool, low luminosity stars with deep convective zones and luminosities that range from \sim 0.0008–0.06L_{\odot} (for dM8–dM0 stars, respectively). These diminutive low mass stars (\sim 0.1–0.6 R_{\odot}; \sim 0.1–0.6 M_{\odot}) have very slow nuclear fusion rates and thus very long lifetimes that range from \sim 40 Gyr for dM0 stars to >200 Gyr for the lower mass, very low luminosity dM5–8 stars. Because of their long stable lifetimes, it is possible that planets hosted by older dM stars could harbor life – possibly even advanced intelligent life. For example, the Sloan Digital Sky Survey has found millions of dM stars as old as, and older than, the Sun (Bochanski et al. 2007). Given their large numbers and long lifetimes, determining the number of dM stars with planets
and assessing planetary habitability is critically important because such studies would indicate how common life is in the universe.

Here we present the initial results of our exploratory pilot program investigating photometry, spectroscopy, and space X-UV observations for a representative sample of ∼40 dM0–6 stars. From this study we have found strong evidence for relations among age, rotation and magnetic activity tracers such as (coronal) X-ray, (transition region / chromospheric) FUV–UV and (chromospheric) Hα emission (Guinan & Engle 2007; Guinan et al. 2007). Utilizing available survey photometry, along with our own, we have identified rotation periods for over 50 dM stars from star spot induced periodic, low amplitude light variations. We have used the ROSAT X-ray and IUE UV archival data and published magnetic field fluxes (Bf) to investigate the X-UV irradiances and their correlations to magnetic field strengths (from Reiners & Basri (2007) and others). This preliminary study has resulted in promising Age-Rotation-Activity relationships for dM0–6 stars. For excellent reviews of the current state of research on – dM star activity and evolution; their suitability as planetary hosts; their impacts on possibly habitable planets and the current planetary search programs including dM star targets – see Scalo et al. (2007); Tarter et al (2007) and references therein. Information about the “Living with a Red Dwarf” Program can be found at http://www.astronomy.villanova.edu/lward/.

2. Motivations for the Program

2.1. Stellar Habitable Zones (HZs)

The temperature of a planet and the circumstellar liquid water HZs for Earth-like planets depend strongly on the luminosity of the host star and the planet’s distance ($1/d^2$) from the star (e.g., Kasting & Catling (2003)). Also important are the planet’s albedo($A$), cloudiness, greenhouse gas heat trapping contributions and the spectral energy distribution of the host star (see Selsis et al. 2007).
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6-7 additional dM planet hosts discovered by Sahu et al. (2006) in the direction of the Galactic Bulge.

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Figure 2. Left – The currently known dM Star Planetary Systems are given along with the properties of the host stars and planets. Right – Illustration of the planet GJ 581c and the effects of either a thick or thin atmosphere.

A relation for estimating the average equilibrium temperature $T_P$ of a rapidly rotating planet ($P_{rot} \leq 3–5$ days) located at a distance ($d$) from the host star with a luminosity of $L$ (in solar units) is given by equation (1).

$$T_P(K) = \frac{279[(1 - A)L_* / L_\odot]^{1/4}}{d^{1/2}} + \Delta T_{GH}$$

(1)

Where $A =$ albedo, $L_* / L_\odot =$ bolometric luminosity of the star relative to the Sun and $d =$ average distance of the hosted planet from the star in Astronomical Units ($1$AU = $1.496 \times 10^8$ km) and $\Delta T_{GH} =$ Greenhouse Effect temperature enhancement (in units of degrees K). For the Earth and Sun: $d = 1.0$ AU, $L_* / L_\odot = 1.0$, $A \approx 0.3$, and $\Delta T_{GH} \sim 31$ K, resulting in the observed average equilibrium temperature of $T_\oplus \approx 286K$ ($= +13^{\circ}C = +55^{\circ}F$). Because of the low luminosities of dM stars, their HZs are located very close to the central star (<0.4 AU). Accordingly, a dM/HZ planet will be more strongly influenced by stellar flares, winds and coronal plasma ejection events that are frequent in young dM stars (e.g. Kasting et al. (1993); Lammer et al. (2007)). As comparison, for an Earth-like planet with an albedo and greenhouse effect similar to the Earth, and hosted by a ~dM2–3 star (with $L_* / L_\odot \sim 0.02$) to have the same average temperature of our Earth, it would have be located $d \approx 0.14$ AU from its host star. This is referred to as the Earth-equivalent distance.

The luminosities of dM stars are essentially constant over tens to hundreds of billions of years after their arrival on the main sequence (Fig. 1b). For this reason, their HZs remain fixed over eons of time, ensuring a stable energy source for hosted planets. By contrast, stars like the Sun undergo significant changes in luminosity on timescales of a few billion years, causing their HZs to move slowly outward over time.

### 3. Extrasolar Planets Around dM Stars

Until the recent theoretical studies of Boss (2006a,b), which showed planets can readily form around dM stars, it was thought that the low masses of dM stars might preclude their formation, due to the expected insufficiently massive protoplanetary disks and possible loss of planets due to lower gravity. Moreover, this
study showed that the majority of dM star planetary systems may be composed of large terrestrial (Earth-like) planets instead of gas giants. Except for a few studies (e.g. Delfosse et al. (1999); Vogt et al. (2000); Endl et al. (2003)), dM stars have not been specifically targeted in major extrasolar planet searches. Nevertheless, planets now have been discovered orbiting eight nearby dM stars using Doppler velocity techniques (Rivera et al. (2005); Forveille et al. (2008)). The properties of these planets are given in Fig. 2a. An increasing number of sub-Neptune mass (< 0.1 M$_J$) planets and “Super-Earths” (defined loosely as planets with masses in the range: 2M$_\oplus$ < $M_P$ sin $i$ < 10 M$_\oplus$) have been discovered to be hosted by dM stars. As pointed out recently by Forveille et al. (2008), there is growing observational evidence that low mass planets (< 0.1M$_J$) may be common around red dwarf stars. For example, at the time of writing, ~1/3 of the 20 known planets with $M_P$ sin $i$ < 0.1 M$_J$ and three of the seven known Super-Earths have been found to orbit dM stars.

Interestingly, one of these stars – GJ 876 (IL Aqr: dM4, d = 4.7 pc) – has been found to host a sub-Jupiter size planet orbiting within its HZ as well as a “Super-Earth” with a mass of only ~7.5 M$_\oplus$ (Rivera et al. 2005). And more recently, using the HST Advanced Camera for Surveys (ACS), several additional dM stars may have been found to host Jupiter-/Neptune-size planets using photometric transit methods (see Sahu et al. 2006). The recent most exciting discovery is that of a large Earth-size planet (GJ 581c: P = 13-d, M ≈ 5 M$_\oplus$, R ≈ 1.5 R$_\oplus$) that orbits within the inner warm edge of the host dM3 star’s HZ. The host star, GJ 581, is already known to harbor a Neptune mass planet and possibly a third planet with a mass of about 8 M$_\oplus$ (Udry et al. 2007). Also see a recent discussion of the habitability of the GJ 581 system by Selsis et al. (2007). Because of its low luminosity, the HZ of GJ 581 lies between ~0.07–0.15 AU from the star. The discovered planet (GJ 581c) orbits ~0.07 AU from its host star and the mean temperature on that planet should range between 0 and 40°C allowing the presence of liquid water on its surface (Udry et al. 2007). Orbiting so close to its host star, though, the planet will become tidally locked ($P_{\text{rot}} = P_{\text{orb}}$). This could initially be thought to hinder habitability. However, Joshi et al. (1997) have shown that a thick enough atmosphere ($P > 0.1$ bar) is capable of transferring heat from the star-lit side of the planet to the dark hemisphere, preventing atmospheric collapse and possibly moderating the global climate (see Fig. 2b). Additionally, Selsis et al. conclude that the more distant planet GJ 581d could also be habitable, given a strong enough greenhouse effect.

4. Preliminary Results of the “Living with a Red Dwarf” Program: Age-Rotation-Activity Relations for dM stars

We are carrying out high precision multi-band photometry of a small sample of dM0–6 stars to determine rotation periods from star spot induced light variations. As found in this study, the rotation period of a dM star is indicative of its age. Young dM stars 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. Unfortunately, reliable ages cannot be determined for dM stars by fitting their observable properties with theoretical evolutionary tracks because these properties ($L$, $T_{\text{eff}}$, $R$) change
very slowly over time in dM stars. However, the ages of some dM stars can be reliably determined from: memberships in nearby star clusters or moving groups (from common kinematic properties) that have reliable ages (almost entirely < 2 Gyr), or from sufficiently high UVW space motions which suggest either Old Disk (6–10 Gyr) or Pop II Halo (>10 Gyr) ages. Another possible method of determining accurate ages for dM stars, though, is from memberships in wide binaries or common proper motion pairs where the more massive/luminous companion star’s age is known from fits to evolutionary tracks. For example, the membership of the nearby 11th mag dM5 star Proxima Cen as an outlying member of the α Cen triple star system has allowed for an accurate age determination from isochronal fits to the G2V system member α Cen A. This has established a reliable age of ~5.8±0.5 Gyr for a star whose age would otherwise be indeterminate. Also, dM stars that are paired with white dwarf companions can have their ages inferred by the white dwarf cooling times. When combined with measures of X-ray, UV and Hα emissions, accurate Age-Rotation-Activity Relationships can be constructed.

Over the last three years we have been carrying out exploratory photometric photometry of a small representative sample of dM0–6 stars to reliably determine rotation periods and star spot properties. The rotation periods are found through low amplitude light variations arising from the presence of star spots. Most of this UBVRI (and in some cases Titanium Oxide (TiO)) photometry is being conducted using the 0.8-m Four College Automatic Photoelectric Telescope (FCAPT) located in Arizona. This study has uncovered low amplitude rotational light modulations (and thus rotation periods) for many of these stars. There is also strong evidence of long-term light variations in some of these stars (e.g. Proxima Cen – P_cyc ≈ 7 yr), indicative of possible solar-like magnetic activity cycles. We have also been searching for light variations in additional equatorial and southern dM stars (and also dK stars) included in the All Sky Automated Survey (ASAS-3; Pojmansk (2001)). Utilizing the powerful period search routines in the latest version of the Period Analysis Software (Peranso – http://www.peranso.com) program, strong evidence of periodicity and possibly
long-term systematic variations in brightness have been uncovered for dozens of additional dM0–6 stars, including Proxima Cen.

Fig. 3a,b illustrates one of the most valuable results of this study – the Age-Rotation-Activity relationships (example given is coronal X-ray activity obtained from the ROSAT archives). Many of the stars with ages \( \leq 2 \) Gyr are members of clusters, moving groups or associations whose ages have been extensively studied and reliably determined. Age estimates for stars older than \(~7\) Gyr have been inferred from their large UVW space motions and galactic orbits. Given the extensive X-ray satellite archives (particularly the ROSAT All-Sky Survey), it is hard to overestimate the value of tight, reliable relationships between dM star X-ray activity and age. The ability to reliably estimate the age of a dM star of known spectral type by measuring the star’s coronal L_x (or f_x) value will be of great use to future studies concerning dM stars. Additional results from our preliminary analysis of FUV-NUV emission lines from the extensive IUE archive have shown just as much potential. These emissions are important for photoionization and photochemical reactions in the upper planetary atmospheres. Also under study are the frequent flares that dM stars display, in which their UV fluxes increase 10–100x for several minutes. The increased X-UV radiation from flares could have adverse effects on the retention of a planet’s atmosphere and be harmful to possible life on its surface.

5. Conclusions & Future Prospects

The “Living with a Red Dwarf” Program, as described here, will benefit the field of extrasolar planets by providing the ages and magnetic evolution (and resulting X-UV emissions) of their host stars. The Age-Rotation-Activity relationships for dM stars found through this program will allow non-program dM stars to have reliably determined ages based on photometric rotation periods or measures of X-ray, UV or Hα emissions (and accurate spectral type for best precision). With the ages of dM star planetary systems reliably known, the dynamic evolutionary history and stability of the system can then be assessed. Furthermore, the past, present and future X-UV radiative environments that the planets will face can be estimated. 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 dM stars are clearly an important issue for future study. Dedicated search programs for planets orbiting dM stars are being developed. For example, the precision radial velocity spectrometer (PRVS – 1 m/s precision in the near-IR) is planned for use on the Gemini telescope by 2011 (Jenkins et al. 2007). Another important ground-based program is the The MEarth Project - a transit survey of \(~2000\) dM stars in the northern hemisphere (Irwin et al. 2008). This project will eventually consist of eight 0.4-m robotic telescopes (two have been in operation since December 2007) and can detect transits by bodies as small as \(~2\) R⊕. Also, space-based planet search missions, including CoRoT and the upcoming Kepler, SIM PlanetQuest and Darwin/TPF Missions are planning to target many additional dM 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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