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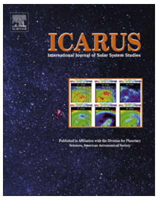

Note

Observations of exoplanets in time-evolving habitable zones of pre-main-sequence M dwarfs

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ABSTRACT

It is recently proposed that planets in the habitable zones (HZ) of pre-main-sequence (PMS) M dwarfs are good targets for the detection of habitable environments. In this note we show that future ground-based telescopes will be able to observe planets in time-evolving HZ of PMS M dwarfs with duration 10–100 Myrs. Based on X-ray measurements, there are >18 M0–M4 PMS stars within 10 pc, the characterization of potentially habitable exoplanets around which could provide highly valuable information regarding the evolution of habitable environments. There are tens of M dwarfs within 10 pc with X-ray to total luminosity ratios similar to that of the young Sun, the observations of potential planets around which could significantly improve our understanding of the physical states of early Solar System rocky planets.

1. Introduction

Because of observation feasibility considerations, M dwarfs are the best places to search for habitable planets and life in the near future. However, the luminosities of M dwarfs decrease by 1 or 2 orders of magnitude during the PMS phase and the consequences of this decrease in luminosity on planetary water inventory and build-up of oxygen atmosphere have recently been discussed (Ramirez and Kaltenegger, 2014; Tian and Ida, 2015; Luger and Barnes, 2015). It is a consensus of these independent studies that the rapid decrease of stellar luminosity moves the planetary HZ inward significantly during the PMS phase and the significant loss of water from rocky planets in the PMS phase could reduce their habitability.

An interesting proposal has suggested that the PMS M dwarfs are good places to search for habitable environments because the orbital distances of PMS HZ of M dwarfs are at large orbital distances and as a result habitable exoplanets are easier to observe (Ramirez and Kaltenegger, 2014). However the observation feasibility of exoplanets around PMS M dwarfs was not discussed. Here we discuss the duration of the PMS HZ, the availability of PMS M dwarfs, and the implications on the observation probability of exoplanets around PMS M dwarfs.

2. Durations of continuous HZ around PMS M dwarfs

As climate model parameters such as cloud properties and coverage contain uncertainties, rough estimates of the inner and outer HZ limits obtained using early Venus and Mars as examples are useful. Ramirez and Kaltenegger (2014) uses the stellar fluxes received by Venus at 1 Gyrs ago (Ga) and Mars at 3.8 Ga, based on the absence and possible presence of surface water on these planets at these ages, to set the inner and outer HZ limits of PMS M dwarfs as functions of time. Using these expressions and parameters, the temporal evolution of the HZ of M dwarfs with 0.08, 0.2, 0.3 and 0.5 solar mass is shown in Fig. 1.

We would like to know how long time a planet around these stars could stay in the HZ continuously, provided that the planet's orbital distance does not change. Migration of planets during the PMS phase is possible through planet–planet scattering, the probability of which is lower around M dwarfs than around more massive stars because of lower probability for giant planets to form around low mass stars (Kennedy and Kenyon, 2008; Johnson et al., 2010). Thus we add vertical dashed lines in each panel to help determine the HZ duration. For a planet at 0.2 AU from a 0.08 solar mass star, it starts to enter the HZ at a proto-planetary disk age of 1 Myrs (inner boundary) and exits the HZ (outer boundary) at an age of 10 Myrs. This is because of the inward movement of the HZ instead of the planet's migration. Thus the duration of HZ at 0.2 AU of a 0.08 solar mass star is 9 Myrs. Following the same logic, the HZ durations, orbital distances, and other parameters corresponding to the vertical dashed lines in Fig. 1 are listed in Table 1.

It is clear that if we would like to observe a planet in a PMS HZ with a duration of 1 Gyrs, the only possibility is for the planet to be at an orbital distance of ~0.041 AU around a 0.08 solar mass star. This distance corresponds to an angular separation of 4 mas if the system is at 10 pc distance. E-ELT is designed to have the capability to obtain contrast of 10^{-9} and angular resolution of ~40 mas (Kasper et al., 2008). TMT's Planet Formation Instrument (PFI) is designed to obtain contrast of 10^{-8} and angular separation of 30 mas (Macintosh et al., 2006). The Second-Earth Imager for TMT (SEIT) is designed to reach 10^{-7} and 10 mas (Matsuo et al., 2012). The capability of SEIT is close to the goal of observing a planet in the PMS HZ with a duration of 100 Myrs around a 0.08 solar mass star at 10 pc. Although the orbital distances of PMS HZ of 0.2, 0.3 and 0.5 solar mass stars are larger and planets in these HZ are potentially observable by these future telescopes, the maximum durations of these stars' PMS HZ, which cannot exceed the duration of PMS phase itself, are 400, 350, and 200 Myrs respectively, significantly shorter than 1 Gyrs. Thus future 30–40-m diameter telescopes will not be able to spatially resolve habitable planets in a Gyr-duration PMS HZ of low mass stars.

On the other hand, future 30–40-m diameter telescopes could observe planets around almost all PMS M dwarfs at 10 pc with HZ duration on the order of 10–100 Myrs. For PMS M dwarfs at 30 pc, only HZ duration on the order of 10–100 Myrs around 0.3–0.5 solar mass stars are possible. How many PMS M dwarfs are there within 10 pc and 30 pc? And what do observations of exoplanets around them require?

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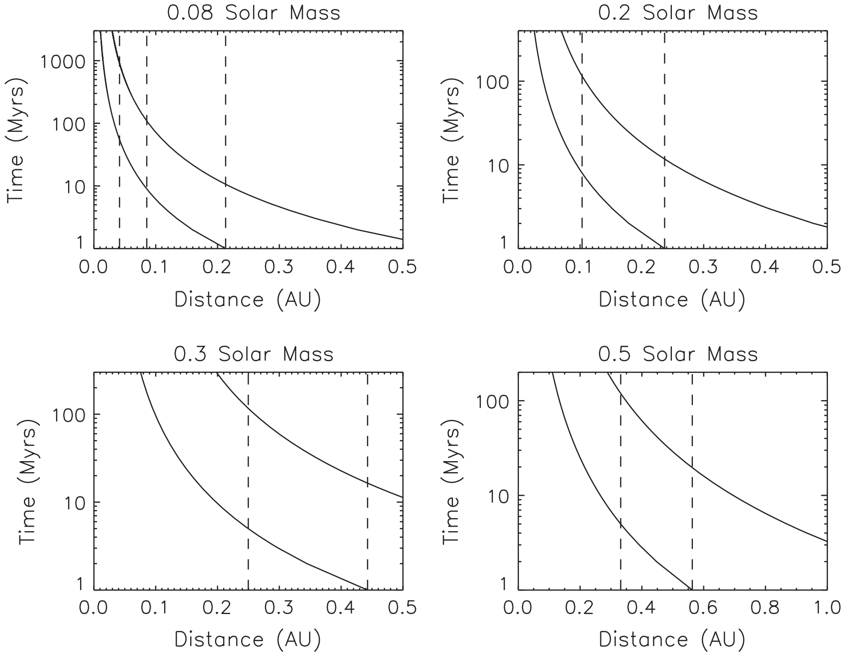

Fig. 1. The time-evolving habitable zones (HZ) of low mass stars. The two solid curves in each panel represent the empirical limits of HZ around different low mass stars according to Ramirez and Kaltenegger (2014). The vertical dashed lines are drawn to help estimate the duration of the HZ at different orbital distances. The PMS phase of 0.2, 0.3, and 0.5 solar mass stars are 400, 350, and 200 Myrs respectively.

Table 1
HZ durations and distances.

Stellar mass (solar mass)	0.08			0.2		0.3		0.5	
HZ duration (Myrs)	1000	100	10	100	15	100	10	100	20
Orbital distance (AU)	0.041	0.085	0.21	0.10	0.24	0.25	0.44	0.33	0.56
Angular separation at 10 pc (mas)	4.1	8.5	21	10	24	25	44	33	56
Angular separation at 30 pc (mas)	1.4	2.8	7.1	3.3	7.4	8.1	15	11	18
Period (Days)	11	32	127	27	94	83	196	98	218
PMS duration (Myrs)[a]	2500			400		350		200	

[a] From Ramirez and Kaltenegger (2014).

3. Future observations of rocky exoplanets around PMS M dwarfs

Lepine and Gaidos (2011, LG11) presented an all-sky catalog of bright M dwarfs (including small percentage of K7 dwarfs). Table 2 lists the spectral type and distance distributions in this catalog. Based on the LG11 catalog there are 309 and 4354 M dwarfs within 10 and 30 pc respectively, consistent with the findings in Matsuo et al. (2012). Although good age estimates of these stars are missing, young stars tend to have stronger X-ray activities (Silvestri et al., 2005; Stelzer et al., 2013). The LG11 catalog includes X-ray count rates for 134 and 806 M dwarfs, within 10 and 30 pc respectively, based on ROSAT/PSPC All-Sky Bright Source Catalog (Voges et al., 1999). In addition, X-ray fluxes of 105 M dwarfs without count rate and within 10 pc distance in the LG11 catalog are reported in Stelzer et al. (2013). We note that the ROSAT/PSPC count rate for a modern solar maximum Sun (X-ray luminosity $L_x = 5 \times 10^{27}$ erg/s) placed at 1 pc would be ~9.5 photons per second (Peres et al., 2000).

Based on the visual magnitudes, parallax, and the X-ray count rates in the LG11 catalog, as well as the X-ray fluxes in Stelzer et al. (2013), the total luminosities (L) and L_x of these stars in comparison with those of the Sun are shown in Fig. 2. The diamonds (group I) and dots (group II) represent M dwarfs in the LG11 catalog within 10 and 30 pc respectively. The triangles represent LG11 M dwarfs with X-ray data from Stelzer et al. (2013). The vertical dotted lines represent the luminosity boundaries of different subtypes of M dwarfs. The L_x of M0–M3 stars are $2\text{–}6 \times 10^{29}$ and 3×10^{28} ergs/s, corresponding to 40–120 and 6 time modern solar L_x, at ages of 10 and 100 Myrs respectively (Stelzer et al., 2013). Thus the shaded area in Fig. 2 marks PMS M0–M3 stars, in which there are 14 PMS M0–M3 stars within 10 pc. If the L_x evolution trend in Stelzer et al. (2013) applies to M4 stars, there are 4 PMS M4 stars within 10 pc. There are more these stars within 30 pc. The names, L_x, and L of the potential PMS M dwarfs within 10 pc are listed in Table 3.

In addition to PMS M dwarfs, observations of main sequence M dwarfs can also provide highly valuable information regarding the early evolution of Solar System rocky planets. The solid, dotted, and dashed tilted lines in Fig. 2 represent the solar L_x/L, at 4.4 billion years ago (Ga), 3.9 Ga, and today correspondingly (Ribas et al., 2005), extrapolated into the L and L_x range for M dwarfs. There are several tens of M dwarfs within 10 pc with L_x/L ratio similar to that of the young Sun. If rocky planets are found in the HZ around these stars, they could resemble early Earth, Venus, and Mars in terms of stellar influences. Because currently we only have indirect evidence (isotopic ratios of H, C, N, O, and noble gases, etc.) of early evolution of Solar System rocky planets, observations of this type of exoplanets will significantly improve our understanding of the physical states of early Solar System rocky planets.

There are multiple ways to observe analogs of early Solar System rocky planets around PMS M dwarfs. If a rocky planet has large amount of water vapor in its atmosphere, its upper atmosphere should contain both H and O. In comparison, a cold rocky planet with a CO_2 dominant atmosphere should have little H in its atmosphere and a planet with little water vapor but large amount of hydrogen should

Table 2
Distance and spectral type distribution in the LG11 catalog.

Distance	K7	M0	M1	M2	M3	M4	M5	M6	M7	M8	M9
⩽10 pc	5	7	19	32	52	71	55	39	22	10	6
10–30 pc	204	380	393	465	1016	1184	339	54	10	0	0
>30 pc	916	1480	1038	761	342	0	0	0	0	0	0