Activity and Kinematics of M and L Dwarfs

John E. Gizis

Infrared Processing and Analysis Center
California Institute of Technology
Pasadena CA 91125 USA

Abstract. I discuss observations of two traditional age indicators, chromospheric activity and kinematics, in late-M and L dwarfs near the hydrogen-burning limit. The frequency and strength of chromospheric activity disappears rapidly as a function of temperature over spectral types M8-L4. There is evidence that young late-M and L dwarfs have weaker activity than older ones, the opposite of the traditional stellar age-activity relation. The kinematics of L dwarfs confirm that lithium L dwarfs are younger than non-lithium dwarfs.

1 Introduction

The Two Micron All-Sky Survey (2MASS) has enabled large samples of cool dwarfs to be detected and studied. Over the spectral range M8 to L8, the traditional TiO and VO molecular bands disappear, grains become important, and the appearance of the spectrum changes drastically [13].

This spectral range, corresponding to temperatures between \( \sim 2300 \) and \( \sim 1400 \)K, covers the crucial transition between hydrogen-burning stars and brown dwarfs. The situation is illustrated in Figs. 1 and 2 using theoretical models [6] and a plausible temperature scale [13]. (See this volume for different views of the L dwarf temperature scale). Both stars and brown dwarfs cool as they contract. Stars, however, eventually stabilize at a constant temperature (the upper tracks in Fig. 1), while brown dwarfs continue to cool (the lower tracks). Current theoretical models suggest that \( 0.075 M_{\odot} \) stars may exist as cool as \( \sim 1800 \)K [4], corresponding to \( \sim \)L4. (In the hotter L dwarf temperature scales, even later L dwarfs may be stars.)

On the basis of Fig. 1, it is clear that field brown dwarfs and stars could be easily distinguished if we could measure age – but age is not directly measurable and must be deduced from indirect measures. Luminosities (in the form of absolute magnitudes) and temperatures (in the form of colors and spectral types), can easily be measured, but as seen in Fig. 2 different mass objects follow evolutionary tracks that are practically indistinguishable.

The need for an age indicator for M and L dwarfs motivates an investigation of two traditional stellar age indicators. Chromospheric activity is linked to age in convective stars through the dynamo: a star is born rapidly rotating, the rotation drives a dynamo which produces magnetic fields, the fields produce activity (chromosphere, corona, flares, and wind) the wind spins down the star,
Fig. 1. Theoretical model tracks for stars and brown dwarfs [6]: Age information allows stars and brown dwarfs to be distinguished.

Fig. 2. Theoretical model tracks for stars and brown dwarfs [6]: Temperatures and luminosities do not provide mass or age information.
the dynamo is weakened, and the observable activity then decreases with age. Kinematics are also linked to age: Stars are born from molecular clouds with low random space velocities, but with time encounters other stars and clouds in the Galactic disk 'heat' the stellar velocity distribution. Most of the discussion in this paper is drawn from Gizis et al. [10].

2 M and L Dwarf Observations

Two large samples form the basis of the discussion in this paper. Late-M and early-L dwarfs have been selected to $K_s < 12$ on the basis of their colors without any kinematic bias [10]. This sample is supplemented by the large sample of fainter L dwarfs also selected on the basis of color [13]. Observationally, a sample of nearby bright M and L dwarfs offers considerable advantages. They are bright enough to relatively easily obtain far-red spectroscopy ($> 6000\AA$), allowing the measurement of spectral types, Hα emission, lithium absorption, surface gravity, and a photometric parallax (Figs. 3, 4, and 5). This can be supplemented by astrometry, providing proper motions, trigonometric parallaxes, and hence tangential velocities. In the case of the late-M dwarfs, the sample is bright enough that the Palomar plates plus 2MASS allow measurements of the proper motions, which Gizis et al. [10] combined with the photometric distance estimate to obtain $v_{tan}$. The Kirkpatrick et al. [13,14] L dwarfs are faint enough that this is not possible, but United States Naval Observatory has measured proper motions and trigonometric parallaxes for a representative sample using CCD astrometry. Together, near-infrared photometry, spectroscopy and astrometry provide a rich set of diagnostics. The discovery of additional bright L dwarfs with $K_s < 12$ will aid many studies, such as 3.3 micron observations of methane (Noll, this volume) and companion searches (Reid, this volume).

3 Activity

The 2MASS samples allow an initial reconnaissance of chromospheric activity in M and L dwarfs. Two critical questions may be addressed: How frequent is chromospheric activity in cool dwarfs? How strong is chromospheric activity?

By adding the spectroscopic survey of nearby stars by Hawley et al. [11], the frequency of activity from K7 ($T_{eff} \approx 4200K$) down to L8 ($T_{eff} \approx 1400K$?) is plotted in Fig. 3. Activity is defined by Hα in emission with equivalent width $> 1\AA$. Two trends are evident. Over the (stellar) range K7 to M7, the frequency of activity increases as cooler, lower-mass stars are considered. The kinematics of field M dwarfs [11] and observations of open clusters [12] both indicate that the active stars are younger than the inactive stars, and that the increase in the frequency of emission reflects the longer lifetime of high activity levels.

The new result by Gizis et al. [10] is to add the cooler (M7-L8) dwarfs, allowing dwarfs at and below the hydrogen-burning limit to be examined. This reveals (Fig. 3) that the frequency of emission declines rapidly from spectral type M8 down to L4 — with cooler dwarfs in these surveys all lacking chromospheric
Fig. 3. Spectra of late-M dwarfs illustrating the richness of molecular features and the Hα emission line at 6563 Å. The M8 dwarf 2MASSW J1047138+402643 (LP 213-68) has much weaker activity than its M6.5 primary 2MASSW J1047126+402643 (LP 213-67).

Fig. 4. KPNO 4-meter spectra of 4 nearby L dwarfs with $K_s < 12$. Even in modest exposure times ($< 30$ minutes), these L dwarfs are accessible to 4-meter telescopes.
Fig. 5. Keck spectra of L dwarfs from Kirkpatrick et al.\cite{14}. Low (9Å) resolution spectra allows both the Hα (6563Å) emission line and lithium (6708Å) absorption line to be observed. L dwarfs with lithium, although young, generally lack Hα emission.

Fig. 6. The frequency of Hα emission for nearby field M and L dwarfs\cite{10,11,14}.
activity. As is evident in Fig. 1, over the range M8 to L4 an increasing fraction of objects will be young brown dwarfs rather than old stars.

The mere presence or absence of detectable Hα emission already reveals interesting behavior, but the declining photospheric emission near 6500Å means that Hα is increasingly easy to detect and equivalent width is a poor measure of Hα’s importance. We therefore plot the strength of Hα emission by considering the ratio of the Hα luminosity to the bolometric luminosity in Fig. 7. The horizontal dotted line indicates the level at which Hawley et al. [11] could detect activity in any M dwarf. It is clear that beyond spectral type M7, even the most active dwarfs would not be considered very strong by the standards of early-to-mid M dwarfs. Furthermore, there is a striking temperature dependence, with the upper envelope of observed activity levels falling by two orders of magnitude over the range M7 to L4. This suggests that effective temperature is the dominant parameter in controlling the activity levels of these cool dwarfs.

![Fig. 7. Activity levels as a function of spectral type for M and L dwarfs. The dotted line at -3.9 is the level at which any M dwarf would be observed in emission. None of the M8 or later dwarfs have activity levels above the -3.9 level, even though such activity is common in mid-M dwarf stars.](image)

4 Adding Age Information

Kinematics provide age information for the M and L dwarf sample. Unlike activity-age relations, where brown dwarfs might not obey the same relations
as stars, the “heating” of the brown dwarf velocity distribution should proceed in the same way as for stars (see [4] for the theory of this process). In particular, young brown dwarfs will tend to have low velocities. The disadvantage of kinematics as an age indicator is that it is only statistical — an old star can have a low random space velocity, with the most notable example being the Sun itself!

The tangential velocities of M8 and M9 dwarfs are compared to their chromospheric activity in Fig. 8. It is striking that the expected stellar age-activity relation is not followed. The population of low velocity ($v_{\text{tan}} < 20 \text{ km/s}$), hence younger, M8 and M9 dwarfs have much weaker emission than the older population with $v_{\text{tan}} > 20 \text{ km/s}$. One obvious explanation would be that the activity levels of the coolest M dwarfs increase with age. However, the theoretical calculations shown in Fig. 1 suggest a different explanation. The young population (corresponding to ages $\lesssim 1 \text{ Gyr}$) are lower-mass stars and brown dwarfs still in their initial cooling phase, while the older, more active population must be hydrogen-burning stars which have largely stabilized at their main-sequence temperature.

![Fig. 8. Emission strength and tangential velocities for M8.0/M8.5 dwarfs (six-pointed stars) and M9.0/M9.5 dwarfs (solid circles). The low-velocity, inactive M dwarfs are a younger population than the high-velocity, active M dwarfs.](image)

For L dwarfs, there is another age and mass diagnostic available in the form of the lithium line[17]. Objects below $\sim 0.06M_\odot$ are never hot enough to destroy lithium and therefore will show a lithium absorption feature, while more massive stars and brown dwarfs will burn up their lithium in nuclear reactions and therefore lack the feature. At a given temperature (spectral type), L dwarfs
with lithium are thus lower-mass and younger than L dwarfs without it (see Fig. 1). Kirkpatrick et al.’s [13] data include both lithium and Hα measurements. Consider the L1-L4.5 dwarfs, where lithium is detectable even at low resolution. Only one early-L dwarf, Kelu 1, shows both Hα emission and lithium absorption. Eleven other such early-L dwarfs show Hα emission but do not have lithium absorption. Twelve early-L dwarfs show lithium absorption but do not have Hα emission (four of these have marginal H detections or noise consistent with emission of less than 2). While many L1-L4.5 dwarfs have neither Hα emission nor lithium absorption, it seems clear that the chromospherically active L dwarfs are drawn from an older, more massive population than the lithium L dwarfs. Beyond L4.5, there are no definite cases of Hα emission, although lithium absorption is present for 50% of the L dwarfs. Overall, the L dwarfs show the same properties as the coolest M dwarfs — the younger, less massive dwarfs are less active than the older, more massive dwarfs, the opposite of the stellar age-activity relation.

These samples, then, lead to a new view of activity near the hydrogen-burning limit. The dominant parameter is effective temperature, with cooler dwarfs, whether stars or brown dwarfs, only being able to maintain lower activity levels. The mass is a secondary parameter, with lower-mass objects having weaker activity at a given temperature, at least for ages typical of field objects. The importance of age, rotation rate, and other parameters needs further investigation.

This new view based on 2MASS field dwarfs can be supplemented with observations of cluster brown dwarfs of known age. In Fig. 9 we plot the activity levels for Pleiades brown dwarfs [18-22] of age ~ 100 Myr with six-pointed stars. Extremely young brown dwarfs from the ρOph [16] and the σOri [23] are also shown. For comparison, the (old) field dwarfs with $v_{\text{tan}} > 20$ km/s are plotted as solid circles and the (young) field dwarfs with $v_{\text{tan}} < 20$ km/s are plotted as open circles.

Despite their youth, activity in the Pleiades brown dwarfs obey the same fall-off with temperature seen in the field dwarfs. Their youth is evidently offset by their lower mass, resulting in unremarkable activity levels. Indeed, no emission is detectable in the Pleiades L dwarf, even though activity is seen in some field L dwarfs of similar spectral type.

The very young (< 10 Myr) brown dwarfs show that the relation between Hα emission and age is not simple. Half of the young cluster brown dwarfs show weak emission, consistent with the field M and L dwarfs, but half show much stronger emission. Like the Pleiades L brown dwarf, the σ Ori L-type brown dwarf has no detectable activity despite its youth. In the case of the ρOph brown dwarf, the mid-IR excess strongly suggests that the emission is due to a disk [16], and Gizis et al. [10] suggest that the 'active' brown dwarfs are actually those with disks, while the relatively inactive brown dwarfs simply show the weak chromospheres expected by analogy with the field dwarfs.

As kinematic information becomes available for more brown dwarfs, it will be possible to test evolutionary models statistically. A first step is shown in Fig. 11.
Fig. 9. The Hα luminosity relative to the bolometric luminosity as a function of spectral type for both cluster brown dwarfs and field dwarfs. Brown dwarfs from the σ Ori cluster (< 10⁷ years), ρ Oph (< 10⁷ years), Pleiades (∼ 10⁸ years) are shown as open squares, open triangles, and six-pointed stars respectively. Note that both cluster L dwarfs have only upper limits on the detected Hα emission. The field M dwarfs are plotted as open circles if $v_{\text{tan}} < 20$ km/s and solid circles for higher velocities.

where tangential velocity is plotted as a function of spectral type. The tangential velocities are based on USNO parallaxes and proper motions (Dahn, priv. comm.). Objects with lithium are shown as open circles, those without lithium are shown as solid triangles. The results are reassuring — the lithium L dwarf population is clearly kinematically cooler, hence younger, than the non-lithium L dwarfs, confirming theoretical expectations. A larger sample will enable trends with spectral type, activity, or other properties to be investigated. Addition of radial velocities will allow the full three-dimensional space velocity distribution to be considered.

5 Further Considerations on Magnetic Activity

Theoretical investigations are needed to understand the temperature and mass dependence of Hα emission from the chromospheres of L dwarfs. Does the lack of emission mean that there is no chromosphere? The latest X-ray observations of an M8 star [8] and M9 brown dwarf [23] indicate that quiescent X-ray coronae are not detectable. The disappearance of coronae is consistent with the observed weakening of the chromosphere. Clearly X-ray observations of L dwarfs would be of great interest to confirm this trend.
Fig. 10. Tangential velocities from U.S.N.O. astrometry for L dwarfs with (open circles) and without (solid triangles) lithium. The lithium L dwarfs have smaller velocities and hence are a younger population.

Although the quiscent activity is already disappearing at M8-M9 spectral types, it is clear that magnetic fields have not entirely disappeared. In Gizis et al.’s [10] spectroscopic survey, 7% of the late-M dwarfs were caught in a flare event. Liebert et al. [15] have reported a huge flare in a 2MASS M9.5 dwarf. Reid et al. [22] observed a flare in the well-known M9.5 dwarf BRI0021, the prototype ‘inactive’ rapid-rotator [3], and also estimate a 7% flare rate. Flaring activity apparently occurs in objects both with and without quiscent chromospheric emission. X-ray flares have also been observed in the M9 brown dwarf LP944-20 [23] with a similar estimated flare rate. Despite the weakening of both the chromosphere and corona, flaring is frequent and strong in the coolest M dwarfs, suggesting that magnetic fields persist. A search for flaring activity among both active and inactive L dwarfs will be of interest, and should naturally occur as ‘standard’ L dwarfs are reobserved. The photometric monitoring reported by Bailer-Jones (this volume) should show whether or not ‘starspots’ exist in these dwarfs.

Two exceptions to the general trend are known. The M9.5 dwarf PC0025 was discovered due to its strong (EW≈ 300Å) Hα emission which has persisted for a decade [24]. Is this a case of a strong chromosphere, or is the emission due to something else? It must be a rare or short-lived phenomenon, since no other field M dwarfs like it have been discovered. More recently, a 2MASS T dwarf has been discovered which has strong, persistent Hα emission [5]. No other T dwarfs, or even late-L dwarfs, have such emission. Is this a chromosphere on a
1000K object, and if so, why is it unique? Other scenarios for the emission are possible.

6 Conclusions

The kinematics of brown dwarfs offer a powerful way to measure ages. Tangential velocities are relatively easy to obtain and should allow the relative ages of M, L, and T dwarf samples to be measured. Preliminary work has already confirmed that lithium L dwarfs are younger than other L dwarfs. Age information should help constrain models of the field brown dwarf mass function which are sensitive to the Galactic star formation history.

For chromospheric activity, there is a good news and bad news. The bad news is that activity is not a very good age indicator. In particular, Hα emission is more likely to be a sign of age in field late-M and L dwarfs than youth, the opposite of the traditional interpretation. The good news is that strong trends are seen in the observations, raising interesting questions. Why do chromospheres — and coronae — disappear at these temperatures? Why is there a mass dependence? Why does flaring persist? What are the unusual objects with strong, persistent emission? The observations beg for theoretical investigations. As new objects are discovered and new observations become possible, we should expect further surprises.

With the completion of 2MASS and further follow-up, new tests of the scenario in this paper will be made. 2MASS has proven to be sensitive to wide L dwarf companions of main sequence stars. Since ages can be independently estimated from the primary star (Kirkpatrick, this volume), tests of the activity-age relation will be possible. Additional cluster brown dwarfs will also be of great help. 2MASS is sensitive to L dwarfs in the Hyades — while an initial search of a portion of the cluster suggests that the Hyades has lost most of its brown dwarfs, it may be hoped that at least one L dwarf remains for 2MASS to discover.

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References

1. Baraffe, I., Chabrier, G., Allard, F., & Hauschildt, P.H. 1998, A&A, 337, 403
2. Basri, G., & Marcy, G.W. 1995, AJ, 109, 762
3. Béjar, V.J.S., Zapatero Osorio, M.R., & Rebolo, R. 1999, ApJ, 521, 671
4. Binney, J. & Tremaine, S. 1987, Galactic Dynamics, Princeton University Press
5. Burgasser, A.J., Kirkpatrick, J.D., Reid, I.N., Liebert, J., Gizis, J.E., & Brown, M.E. 2000, AJ, 120, 473
6. Burrows, A., et al. 1997, ApJ, 491, 856
7. Fleming, T.A., Giampapa, M.S., & Schmitt, J.H.M.M. 2000, ApJ, 533, 372
8. Gizis, J.E., Reid, I.N., & Monet, D.G. 1999, AJ, 118, 997
9. Gizis, J.E., Monet, D.G., Reid, I.N., Kirkpatrick, J.D., & Burgasser, A.J. 2000, MNRAS, 311, 385
10. Gizis, J.E., Monet, D.G., Reid, I.N., Kirkpatrick, J.D., Liebert, J., & Williams, R.J. 2000, AJ, 120, 1085
11. Hawley, S.L., Gizis, J.E., & Reid, I.N. 1996, AJ, 112, 2799
12. Hawley, S.L., Reid, I.N., Gizis, J.E., & Byrne, P.B. 1999, ‘Chromospheric Activity in Low Mass Stars: Observational Results from Clusters and the Field’. In: Solar and Stellar Activity: Similarities and Differences, ASP Conference Series 158, ed. C. J. Butler & J. G. Doyle., p.63
13. Kirkpatrick, J.D., Reid, I.N., Liebert, J., Cutri, R.M., Nelson, B., Beichman, C.A., Dahn, C.C., Monet, D.G., Gizis, J.E., & Skrutskie, M.F. 1999, ApJ, 519, 802
14. Kirkpatrick, J.D., Reid, I.N., Gizis, J.E., Burgasser, A.J., Liebert, J., Monet, D.G., Dahn, C.C., & Nelson, B. 2000, AJ, 120, 447
15. Liebert, J., Kirkpatrick, J.D., Reid, I.N., & Fisher, M.D. 1999, ApJ, 519, 345
16. Luhman, K.L., Liebert, J., & Rice, G.H. 1997, ApJ, 489, L165
17. Maguzzu, A., Martín, E.L., & Rebolo, R. 1993, ApJ, 404, L17
18. Martín, E.L., Rebolo, R., & Zapatero-Osorio, M.R. 1996, ApJ, 469, 706
19. Martín, E.L., Basri, G., Gallegos, J.E., Rebolo, R., Zapatero Osorio, M.R. 1998, ApJ, 499, L61
20. Martín, E.L., Basri, G., Zapatero Osorio, M.R., Rebolo, R., & Garcia Lopez, R.J. 1998, ApJ, 499, L41
21. Reid, I.N., Kirkpatrick, J.D., Liebert, J., Burrows, A., Gizis, J.E., Burgasser, A., Dahn, C.C., Monet, D., Cutri, R., Beichman, C.A., Scutrokskie, M. 1999, ApJ, 521, 613
22. Reid, I.N., Kirkpatrick, J.D., Gizis, J.E., & Liebert, J. 1999, ApJ, 527, L105
23. Rutledge, R.E., Basri, G., Martín, E.L., & Bildsten, L. 2000, ApJ, 538, L141
24. Schneider, D.P., Greenstein, J.L., Schmidt, M., & Gunn, J.E. 1991, AJ, 102, 1180
25. Zapatero Osorio, M.R., Rebolo, R., Martín, E.L., Basri, G., Maguzzu, A., Hodgkin, S.T., Jameson, R.F., & Cossburn, M.R. 1997, ApJ, 491, L81
26. Zapatero Osorio, M.R., Bejar, V.J.S., Rebolo, R., Martín, E.L., & Basri, G. 1999, ApJ, 524, L115