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ROTATION AND ACTIVITY AMONG SOLAR-TYPE STARS OF THE URSA MAJOR GROUP[1]

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ABSTRACT

We examine rotation and chromospheric activity among G and K dwarfs recently shown to be members of the Ursa Major Group (UMaG). Rotation periods for UMaG stars are smaller than for stars of the same colors in the Hyades, and by an amount corresponding to the Skumanich relation ($\Omega \propto t^{-1/2}$, t = age). Most UMaG stars have about the same level of Ca II and K emission, implying that they also have nearly uniform intrinsic rotation rates. That means that the diversity of rotation rates and levels of activity seen among solar-type stars in the α Persei and Pleiades clusters (a range of ~1.5 dex) has largely converged (to $\lesssim$0.1 dex) by the age of UMaG (0.3 Gyr).

Subject headings: open clusters and associations: individual (Ursa Major Group) — solar neighborhood — stars: activity — stars: kinematics — stars: late type — stars: rotation

1. INTRODUCTION AND OBSERVATIONS

The evolution of angular momentum and chromospheric activity in stars like the Sun is complex. Once a star is more than about 1 Gyr old, it is well behaved, and these properties appear to decline with age in a predictable fashion. The precise relationships between rotation, activity, and age are not yet known precisely, but they at least appear to be deterministic (Soderblom, Duncan, & Johnson 1991). But when solar-type stars first reach the zero-age main sequence (ZAMS), their rotation rates and levels of activity can range over an order of magnitude or more. For example, both the α Persei and Pleiades clusters, with ages of 50 and 70 Myr, respectively, have solar-mass stars with surface rotation rates ($v \sin i$) from less than 7 up to 100 to 200 km s^{-1}, that is, they span a range of as much as 1.5 dex (Stauffer et al. 1984, 1985). The spread in rotation in these clusters, although measured as $v \sin i$, cannot be due to projection effects alone (Soderblom et al. 1993a, hereafter SSHJ). By the time those stars are as old as the Hyades (0.6 Gyr), their range in rotation periods is only 0.1 dex (Radick et al. 1987).

This remarkable convergence in rotation is accompanied by a comparable lessening of the range of chromospheric emission (CE) seen within those clusters (Soderblom et al. 1993a, b; Soderblom & Clements 1987). Recent theoretical models (Pinsonneault et al. 1989, 1990; MacGregor & Brenner 1991) attempt to treat this convergence, though not usually to the degree that it is observed. Further observations can provide more constraints on the models, and so it is natural to ask how solar-type stars behave at an age that is between those of the Pleiades and Hyades.

Nature has not provided a nearby, well-populated open cluster with an age of 0.2 or 0.3 Gyr that can be studied in the same detail that is possible for the Pleiades and Hyades, but we are in the midst of a loose and sparse group of stars that reveal their common origin through their common kinematics. This is the Ursa Major Group (UMaG), whose known members are mostly within 25 pc. Activity and rotation among UMaG solar-type stars have already been examined (Soderblom 1983; Walter et al. 1984; Schmitt et al. 1990), but those studies were hampered by uncertainty about the membership of individual stars in the Group.

We have just completed a membership study of solar-type stars in UMaG (Solderblom & Mayor 1993, hereafter SM) in which we required candidate members to exhibit levels of CE at least as great as that seen in the Hyades, in order to restrict members to the genuinely young stars. (In practice this meant that SM required R'_{HK} to exceed −4.6; see Fig. 2.) Those candidates meeting the spectroscopic criteria turned out to have tight, well-defined kinematics that agreed with the motion of the Group's nucleus. Only one star passed the spectroscopic tests whose motions failed to agree with those of the nucleus, and only one star (HD 88355 = 34 Leo) had appropriate kinematics but too little activity. It is not surprising that one or two older field stars would fall within UMaG's region of velocity space just by chance (see, e.g., Soderblom 1990), so we believe it unlikely that 34 Leo is a genuine UMaG member. One other star (HD 147584 = ζ TrA) was retained as a possible member because it had kinematics appropriate to UMaG, but its activity could not be compared to the other candidates because it is a close binary ($P_{orb} \approx 13$ days) that is probably tidally synchronized (its $v \sin i$ is consistent with this period). Whether or not ζ TrA is a member, its duplicity means that it cannot be used to say anything about rotation or activity among the stars of the Group because both quantities in this instance are not age-related.

SM present a complete list of Group candidates and likely members (as well as remarks on the individual stars that will not be repeated here). In this *Letter* we reexamine rotation and CE among the solar-type stars that were judged to be probable members; those stars are listed in Table 1. The sources of information and details on the analysis of the chromospheric data are given in SM. R'_{HK} is the ratio of the star's Ca II H and K emission flux to its bolometric flux, after correction for

[1] Based in part on observations obtained at the Mount Wilson Observatory, at Lick Observatory, and on archival data from the *International Ultraviolet Explorer*. Also based on data from the SIMBAD retrieval system, a data base of the Strasbourg, France, Astronomical Data Center.

TABLE 1

ROTATION AND ACTIVITY IN UMaG SOLAR-TYPE STARS

HD (1)	HR (2)	Name (3)	Spectral Type (4)	$(B-V)$ (5)	T_{eff} (6)	log R'_{HK} (7)	log R_{hk} (8)	log $R_{H\alpha}$ (9)	$v \sin i$ (10)
			Probable Members						
11131	...	χ Cet B	dG1	0.62	5800	−4.37	−4.28	−4.95	3.4±1.7
13959	...	...	K4V	1.05	4480	−4.35	−4.29	−4.94	5.0±0.6
26913	1321	V891 Tau	G8V	0.70	5500	−4.39	−4.19	−4.90	4.4±0.7
26923	1322	V774 Tau	G0V	0.59	5920	−4.49	...	−5.01	3.7±1.0
39587	2047	χ^1 Ori	G0V	0.59	5920	−4.44	−4.22	−4.95	9.0±0.2
41593	...	...	K0Ve	0.81	5140	−4.42	−3.91	−4.90	4.0±0.5
72905	3391	π^1 UMa	G1V	0.62	5800	−4.33	−4.16	−4.76	9.7±0.4
109011	...	...	K2V	0.93	4780	−4.35	−4.38	−4.70	5.2±0.3
109647	...	...	K0	0.95	4740	...	−4.27	−4.65	2.3±2.0
110463	...	...	K3V	0.95	4740	...	−4.28	−4.93	2.1±1.1
111456	4867	...	F6V	0.46	6480	−4.39	−4.24	−4.92	35
115043	...	...	G2V	0.60	5880	−4.43	−4.10	−5.05	7.5±0.3
141003B	5867B	β Ser B	dK3	0.99	4900	...	−4.17	−4.6:	3.3±1.5
147513A	6094A	...	G5V	0.62	5800	−4.40	−4.24	−4.97	3.3±0.6
165185	6748	...	G3V	0.62	5800	...	−4.19	...	7.5±0.7
			Possible Members						
88355	3998	34 Leo	F7V	0.46	6480	...	−5.00	...	18.1±1
147584	6098	ζ Tra	G0V	0.55	6080	−4.4:	−4.52	...	≤3.0

photospheric light in the instrumental bandpasses (Noyes et al. 1984). R_{hk} is a similar ratio for the Mg II h and k ultraviolet lines (from *IUE* observations), and $R_{H\alpha}$ is the flux ratio for the chromospheric component of Hα, taken from SM. The $v \sin i$ values in column (10) are derived from CORAVEL observations (Benz & Mayor 1984) and agree well with values from line-profile analyses (Soderblom 1982). SM also confirm the traditional age for UMaG of 0.3 Gyr.

We emphasize that UMaG membership was based on both kinematics and activity and that what we demonstrated in SM was that activity could be used to select candidates that would have an excellent chance of being genuine Group members. We will include 34 Leo and ζ TrA in the discussion so that the reader may judge whether or not they constitute contradictions to what is seen among the probable members, and to avoid circular reasoning in this discussion of activity within the Group.

2. DISCUSSION

Figure 1 compares the rotation of UMaG stars to that of similar stars in the Hyades. The Hyades data are taken from SSHJ and consist of $v \sin i$ determinations from Kraft (1965, 1967) and Soderblom (1982) (open symbols), as well as measurements of rotation periods converted to $v \sin i$ (filled symbols, from Radick et al. 1987). The $v \sin i$ values derived from P_{rot} were all reduced by a factor of $\pi/4$ to make them compatible with the other $v \sin i$ values in a statistical sense. The two groups of stars may have slightly different mass-color relations because of their different metallicities, but that is compensated for by the structure of the stars being similar at the same color (at 1.0 $M_\odot$, say, a Hyades star is redder than an UMaG star because [Fe/H] is greater in the Hyades, but the Hyades star also has a deeper convective envelope, which appears to be a key determinant of activity and angular momentum loss).

We first consider the seven UMaG stars at $(B-V) \simeq 0.60$, for which $\langle v \sin i \rangle = 6.4$ km s^{-1}. For 10 Hyades dwarfs from 0.58 to 0.64 in $(B-V)$, $\langle v \sin i \rangle = 6.7$ km s^{-1}. These averages are essentially identical and suggest that these ~1.1 $M_\odot$ stars have undergone little or no rotational evolution from the age of UMaG to the age of the Hyades. But rotation periods tell a more accurate story, for they are free of the aspect ambiguity inherent in using $v \sin i$ data. At $(B-V) = 0.60$ in the Hyades, $\langle P_{rot} \rangle = 7.3 \pm 0.3$ days (Radick et al. 1987). In UMaG, we know that the rotation period of χ^1 Ori is 5.1 days (Stimets & Giles 1980). If these youthful Suns behave in accord with the Skumanich relation, we expect the ratio of the rotation periods to equal the square root of the ratio of the ages (because $\Omega \propto t^{-1/2}$; Skumanich 1972), and, in fact, $7.3/5.1 = 2^{1/2}$. (A line

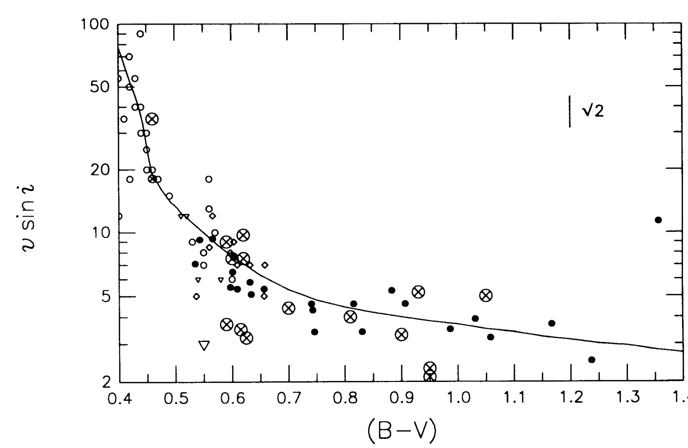

FIG. 1.—Measurements of $v \sin i$ (km s^{-1}) vs. $(B-V)$ color. The large circles with crosses in them represent Ursa Major Group probable members from Table 1, while the smaller circle with a cross represents the possible member HD 88355, and the large triangle represents the upper limit to $v \sin i$ for HD 147584. The other points are for stars of the Hyades and represent $v \sin i$ data from Kraft (1965, 1967; *open circles*) and Soderblom (1982, *open diamonds*), and rotation periods converted to $v \sin i$ (from Radick et al. 1987). The curve is a mean relation for the Hyades drawn through the points (ignoring the reddest Hyades star shown).

of length $2^{1/2}$ is shown in Fig. 1 to indicate the difference anticipated between the two groups of stars if the Skumanich relation pertains.)

Does χ^1 Ori rotate at a representative rate, or is it just one of the fastest spinning stars in UMaG? Two pieces of evidence suggest the former. First, a preliminary rotation period of 4.1 days is now available for π^1 UMa (E. F. Guinan & G. P. McCook 1992, private communication). That in itself is inconclusive, since χ^1 Ori and π^1 UMa have the two largest $v \sin i$ values in the Group, and their $P_{\rm rot}$ values just confirm their rapid rotation. But the early-G dwarfs in UMaG also have very uniform levels of CE. This can be seen in the lower panel of Figure 2, where we compare Ca II H and K emission in UMaG to the Hyades (the data for the latter were taken from Duncan et al. 1991 for stars with nine or more observations and converted to $R'_{\rm HK}$ with the prescriptions in Noyes et al. 1984). For the six UMaG stars at $(B-V) \simeq 0.60$ that have Mount Wilson observations of Ca II H and K, $\langle \log R'_{\rm HK} \rangle = -4.41 \pm 0.06$. At the same color in the Hyades, $\langle \log R'_{\rm HK} \rangle = -4.49 \pm 0.04$ (Soderblom 1985). The $\langle \log R_{\rm hk} \rangle$ values at this color in the two clusters have similarly low spreads (Soderblom 1985). The good and consistent correlation between rotation and activity seen in solar-type stars, even those as young as the Pleiades (SSHJ), implies that the intrinsic rotation rates of these UMaG G dwarfs have as little variance as is seen among the Hyades G dwarfs. In other words, uniformity of CE argues for uniformity of Ω and indicates that the low $v \sin i$ values of some UMaG members is just due to their $\sin i$, not to low $v_{\rm rot}$. Within UMaG itself, the ratio of rotation periods of χ^1 Ori and π^1 UMa equals the ratio of their activity indices, again supporting the proportionality of rotation and activity. HD 26913,

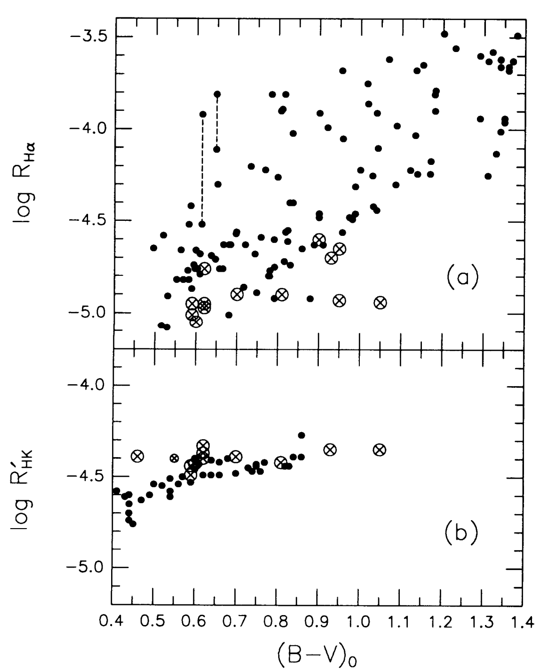

FIG. 2.—(*a*) Comparison of Hα chromospheric emission for stars of the Pleiades (SSHJ, *solid points*) and UMaG (SM, *large circles with crosses*). $R_{\rm H\alpha}$ is the ratio of the star's Hα chromospheric flux to its bolometric flux. W_λ(Hα) was measured and converted to a flux by methods detailed in SSHJ. The two dashed lines connect two values for two Pleiads that have broad Hα emission that extends into the wings. (*b*) The $R'_{\rm HK}$ indices for UMaG stars (*circles with crosses*) and Hyades members (*filled circles*).

at $(B-V) = 0.70$, adds corroborating evidence. It has $P_{\rm rot} =$ 7.2 days (Baliunas et al. 1983), whereas $\langle P_{\rm rot} \rangle \approx 9$ days in the Hyades (there are no stars at $[B-V] = 0.7$ in the Hyades that have measured rotation periods, so this mean was estimated from Fig. 4 in Radick et al. 1987).

Unless some of the early-G dwarfs are conspiring to generate high levels of activity while rotating slowly, the intrinsic rotation rates of those stars must be about the same as the stars with large $v \sin i$ (χ^1 Ori and π^1 UMa). The simplest explanation, then, of what we see among these Ursa Major Group solar-type stars is that they all rotate at rates $\sim 2^{1/2}$ times that of a Hyades dwarf of the same color. And that means that the huge spreads in rotation and activity seen among solar-type stars in the α Persei and Pleiades clusters have converged to a small range by an age of about 0.3 Gyr, or within $\sim$200 Myr. The ultra-fast rotators of the α Persei and the Pleiades (stars with $v \sin i \gtrsim 30$ km s^{-1}) are not seen in UMaG.

This conclusion is weakened by the small size of our sample but is unaffected by whether or not the possible members are included (34 Leo is much bluer than the other stars considered here, and ζ TrA is a close binary whose rotation and activity can be interpreted in age-related terms). It can be strengthened if rotation periods are determined for more of the stars of Table 1, which should be relatively easy, given that these stars are bright and these young stars often show significant photometric variability. Enlargement of the sample, either by adding more UMaG members or by observing a more distant cluster of similar age, would also help. For example, NGC 6475 and 7092 have ages between those of the Pleiades and Hyades and are part of the CORAVEL surveys of open clusters (M. Mayor & J.-C. Mermilliod 1992, private communication). Some stars that are about 150 Myr old also need to be observed to further constrain the time scale on which these stars converge in rotation and activity.

As we noted, Ca II H and K and Mg II *h* and *k* emission are at nearly uniform levels among these stars and are consistently above what is seen in the older Hyades dwarfs (Fig. 2). Little HK or *hk* data are available for the Pleiades to allow a similar comparison, but in Figure 2 we illustrate the $R_{\rm H\alpha}$ values of UMaG members (from SM) with Hα flux ratios for stars of the Pleiades (from SSHJ). The uncertainty in W_λ(Hα) is about 15 mÅ (SSHJ), corresponding to about 0.06 dex for the typical W_λ seen in one of these stars (both the UMaG and Pleiades observations were made with the same instrument and analyzed in the same way). Even if that error estimate is optimistic, the relative errors in Figure 2 are small and cannot alter the conclusion that there is some overlap in the range of $R_{\rm H\alpha}$ seen in the Pleiades and in UMaG, even if most Pleiads have much stronger Hα emission than do stars of UMaG. The same statement can be made about data for the Ca II infrared triplet lines.

ROSAT data may reveal more UMaG members in the solar neighborhood, as may the results from *Hipparcos*. For the present, little can be said about the coronae of UMaG stars because so few true members have been studied in X-rays. Walter et al. (1984) and Schmitt et al. (1990) examined *Einstein* observations for UMaG candidates, but, once attention is restricted to bona fide members, only three solar-type stars are left (χ^1 Ori, π^1 UMa, and HD 111456), all of which have $\log L_x \approx 29$. Those Pleiads actually detected by *Einstein* have $\log L_x > 29$, but there may be many Pleiads with $\log L_x < 29$ (Micela et al. 1990). At the same time, there are a number of Hyades solar-type stars with $\log L_x > 29$ (Micela et al. 1988).

It appears that X-ray emission is a looser function of age than is emission arising from the chromosphere.

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