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STELLAR ROTATION IN THE HYADES AND PRAESEPE: GYROCHRONOLOGY AND BRAKING TIMESCALE

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Abstract. We present the results of photometric surveys for stellar rotation in the Hyades and in Praesepe, using data obtained as part of the SuperWASP exoplanetary transit-search programme. We determined accurate rotation periods for more than 120 sources whose cluster membership was confirmed by common proper motion and colour-magnitude fits to the clusters' isochrones. This allowed us to determine the effect of magnetic braking on a wide range of spectral types for expected ages of $\sim$ 600 Myr for the Hyades and Praesepe. Both clusters show a tight and nearly linear relation between $J - Ks$ colour and rotation period in the F,G and K spectral range. This confirms that loss of angular momentum was significant enough that stars with strongly different initial rotation rates have converged to the same rotation period for a given mass, by the age of Hyades and Praesepe. In the case of the Hyades our colour-period sequence extends well into the M dwarf regime and shows a steep increase in the scatter of the colour-period relation, with identification of numerous rapid rotators from $\sim$0.5 $M_{\odot}$ down to the lowest masses probed by our survey ($\sim$0.25 $M_{\odot}$). This provides crucial constraints on the rotational braking timescales and further clears the way to use gyrochronology as an accurate age measurement tool for main-sequence stars.

Keywords: stars: rotation; stars: open clusters; Hyades, Praesepe

1 Candidate selection

1.1 Observations

We determined stellar rotation rates using data from the SuperWASP camera array, located at the Observatorio del Roque de los Muchachos on La Palma, Canary Islands. With its 8 cameras, SuperWASP (described in detail in Pollacco et al. 2006) has a total field of view of 640 deg^2. This extremely wide field of view provides the ability to make repeated observations of areas of the sky as large as the full Hyades cluster, providing densely sampled photometric data. The corresponding fields were observed between 25 and 100 times per night on average, with typically 5 to 10 minutes between each 30s exposure. The data was reduced by the standard WASP pipeline, described in detail by Pollacco et al. (2006); Collier Cameron et al. (2009, hereafter CC09). Each SuperWASP source is matched with NOMAD and Hipparcos data, providing high signal to noise photometry in the standard $BVJHK$ bands, proper motion as well as parallax when available. SuperWASP photometric data itself is only used to derive the rotation period from the photometric rotational modulation of the signal due to stellar spots.

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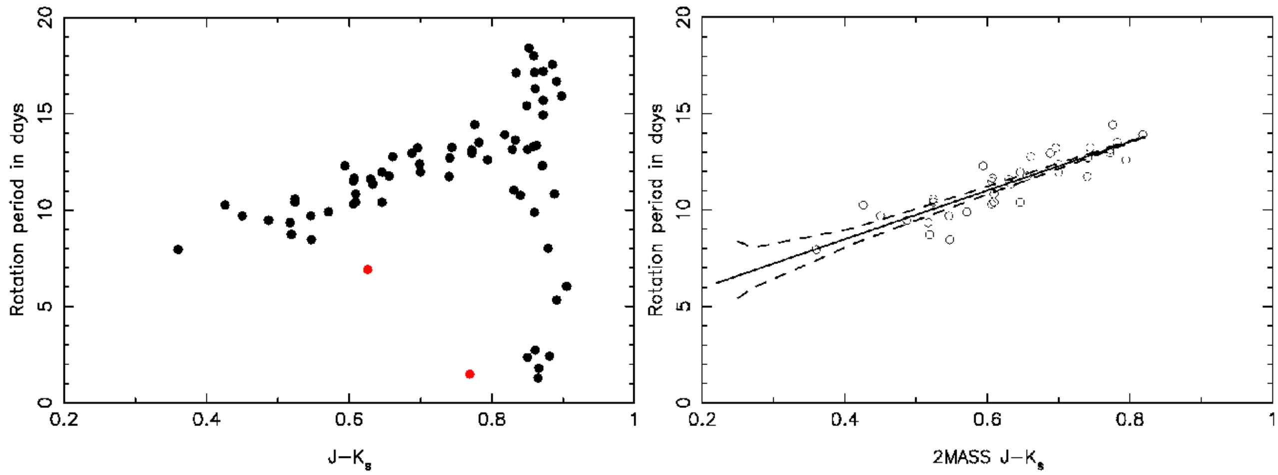

Fig. 1. *Left:* $J - K_s$ colour-period plot of all selected Hyades members. The 2 outliers highlighted in red are known spectroscopic binaries. *Right :* $J - K_s$ colour-period plot of Hyades members that are used to derive the colour-period relation (black line). The dashed lines represent the expected spread in periods caused by differential rotation (see CC09 for details).

1.2 Light curve analysis

We used the generalised Lomb-Scargle periodogram formulation of Zechmeister & Kürster (2009) to look for quasi-sinusoidal light curve modulation in all stars in the fields. The details of the frequency analysis and the optimised False Alarm Probability (FAP) calculation we used are described by CC09. We looked for signal modulation due to rotation periods between 1.1 days and 20 days and selected only signals with a FAP<0.05.

1.3 Cluster membership

Each source with a detected period was examinated to determine whether or not it was a cluster member. A cluster membership probability was derived by comparing the proper motion and the apparent magnitudes of each candidate to those expected for Hyades or Praesepe members. This was carried out assuming Gaussian distribution of both population and weighted by the relative number of stars in the field and in the cluster to take into account that there are many more field stars than cluster stars in our sample. As in CC09, we extended this definition of cluster membership to include information on the apparent magnitude and the same rationale was applied to determine whether the colour and apparent magnitude of each source was closer to the field distribution or to the colour magnitude relation expected for each cluster. After a visual examination of all selected variable cluster members, we retained 70 Hyades members and 52 Praesepe members with a reliable measured rotation period.

1.4 Period-colour relation

To derive a clean period-colour relation, we selected the reliable candidates which sit in the $0.2 < J - K_s < 0.82$ colour range, where Hyades and Praesepe members appear to follow a smooth colour-relation. Since higher order fits did not improve the correlation, we used a simple linear fit to find the period-colour relation.

The relations derived are the following :

$$P_{Hyades} = 11.401 + 12.652\,(J - K_s - 0.631) \quad (1.1)$$

$$P_{Praesepe} = 9.648 + 12.124\,(J - K_s - 0.528) \quad (1.2)$$

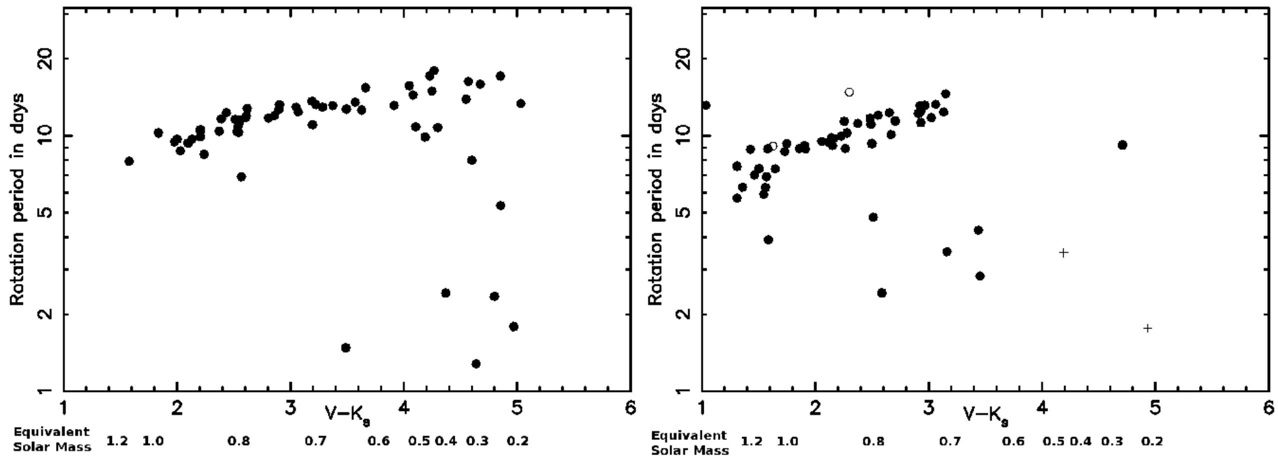

Fig. 2. *Left:* Log of rotation period-$V - K_s$ colour plot of objects identified as Hyades members. *Right:* Same for Praesepe members. The crosses are 2 Praesepe objects from Scholz & Eislöffel (2007). Full circles are objects with a membership probability above 0.85, hollow circles are objects with a membership probability above 0.5.

2 Comparison between the Hyades and Praesepe: age and braking.

2.1 Braking timescales

Deriving stellar rotation braking timescales over a wide range of stellar masses, and especially in the M-dwarf regime where stars become entirely convective, puts strong constraints on theoretical models of magnetic field/rotational braking. As seen in Fig. 1, our survey determined rotation periods of M-dwarf stars both in the Hyades and Praesepe. However, these figures use the $J - K_s$ colour that tend to saturate for the reddest stars ($J - K_s$ only varies from 0.82 to 0.86 when the stellar mass varies from 0.6 $M_\odot$ to 0.25 $M_\odot$) that are the most interesting to explore rotational braking timescales. Fig. 2, shows the logarithmic rotation period as a function of the $V - K_s$ colour.

For the Hyades this breakdown is obvious because we have a good sampling at low masses: the cluster is nearby and its M-dwarfs are bright enough to derive reliable rotation periods. It seems to occur for $V - K_s >$ 4.0 (i.e. masses $\lesssim 0.5 M_\odot$), with the apparition of numerous fast rotators as well as a significant increase of the slow rotators scattering around the colour-period relation. The Hyades data therefore demonstrate that FGK and M stars above 0.5 $M_\odot$ have converged toward a simple colour-period relation by Hyades age, about 625 Myr.

The breakdown of the period-colour relation is less clear-cut for Praesepe because this cluster is farther away and the survey detection limit is in the late K/early M-dwarf range. It is however clear that objects redder than $V - K_s$=3.2 (or below 0.65 $M_\odot$) have converged toward a the colour-period relation by Praesepe age and it appears that Praesepe stars rotation rate have clearly converged for masses higher than 0.65 $M_\odot$ and have not converged in the mid/late M dwarf range (see Scholz & Eislöffel 2007). The colour-period relation breakdown in Praesepe must then occur in between, in the 0.65–0.4 $M_\odot$ mass range.

2.2 Relative age of Praesepe compared to the Hyades

Barnes (2003) coined the word "gyrochronology" to describe the technique that permits us to derive the age of a star when its rotation period is known. This assumes, following the early study of Skumanich (1972), that the rotation period of stars of given mass converges after a certain time to the same value independently of the initial conditions and that their rotation period then evolves following a simple $t^{-1/2}$ spindown law. The data presented here confirms that Hyades and Praesepe stars with $0.2 < J - K_s < 0.82$ have already converged toward a well defined colour-rotation period relation.

Any star in this colour range can have its period, and thus its age, derived with respect to an age/rotation

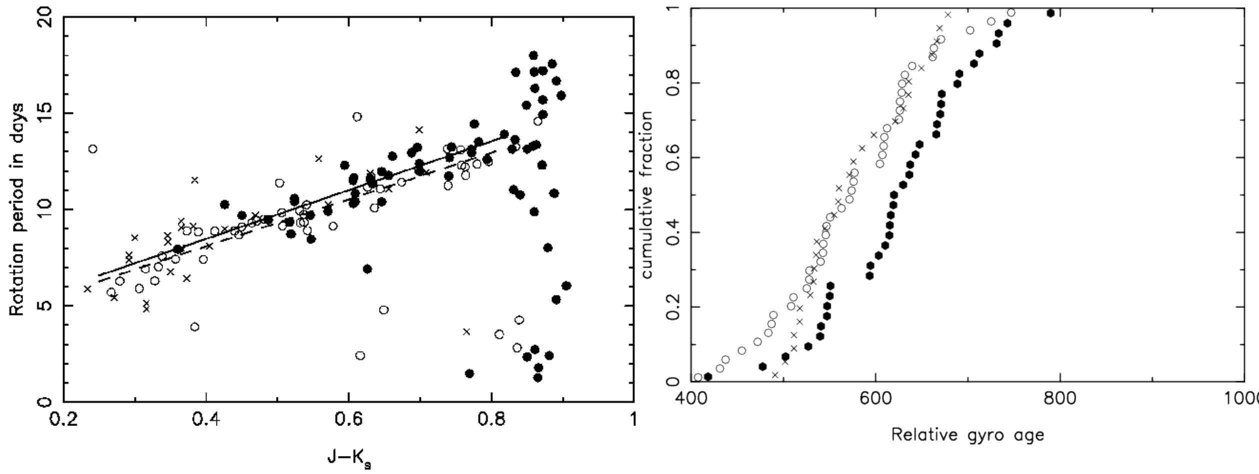

Fig. 3. *Left:* $J - K_s$ colour-period plot of Hyades (black circles for SWASP objects and crosses for R87-95 objects) and Praesepe members (hollow circle). The period-colour relation are also shown, black line for the Hyades and dashed line for Praesepe. *Right:* Cumulative fraction plot of Hyades members ages (black circles), Praesepe members ages (hollow circles) and Coma members ages (crosses)

reference. To derive Praesepe's age relatively to the Hyades, we anchored the age-period relation assuming a mean Hyades age of 625 Myr (P98). We derived the age of Praesepe stars by computing the rotation period they would have if they had the age of Hyades and comparing this hypothetical period to the measured one we were able to compute an age for each slow rotator in Praesepe as follows:

$$t \;=\; 625\left(\frac{P}{11.401\,+\,12.652\,(J-K-0.631)}\right)^2 \,. \tag{2.1}$$

The age of Praesepe was derived from the averaged ages of these 43 stars, and stands at 578±12 Myr. This absolute value needs to be taken with caution since the uncertainties on the actual Hyades age, that we use to anchor the relation, are much bigger (± 50 Myr Perryman et al. 1998) than our errors. However, the relative measurements are much more reliable and a Student T-test on these $0.2 < J - K_s < 0.82$ samples showed that there is only 1.5% likelihood they derive from the same age distribution. Using our new SWASP data for the Hyades and CC09 data for the Coma cluster, we also derived an improved estimation of Coma's age: 584±10 Myr.

2.3 Individual stars age distribution relative to Hyades age

Fig. 3 shows the ages of individual stars in our sample for each of these 3 clusters. The large scatter in ages observed on this figure is likely not real but most of it is probably due to the scatter of the colour-period-age relation at about 600 Myr. This scatter is 85 Myr for the Hyades, 85 Myr for Praesepe and 61 Myr for Coma (respectively 76 Myr, 77 Myr and 55 Myr with the improved gyrochronological relation), showing that at these ages the simple gyrochronology spin-down law from Skumanich (1972) enables age measurements for individual stars with a better than 15% accuracy, improving as the square root of the number of cluster members when measuring the age of a cluster. If this relation is properly calibrated for field stars, gyrochronology should provide even more accurate age measurements for individual field stars because the scatter of the colour-period-age relation is expected to decrease with age.

3 Conclusion

We presented an analysis of SWASP data that found more than 120 rotational variables that we identified as Hyades and Praesepe cluster members. This allowed us to put strong constraints on the rotational braking time by showing that the periods of all FGK and M single stars down to $\sim$0.5 $M_\odot$ in our sample have converged toward a relatively tight period-colour relation by Hyades age. We used gyrochronological relations and the period-colour relations derived for each cluster to accurately measure their relative ages, assuming the Hyades are 625

Myr old. This yields ages of 578±12 Myr for Praesepe and 584±10 Myr for Coma and gives a statistically strong statement that Praesepe and the Hyades are not exactly co-eval and that the former is 47±17 Myr younger than the latter.

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