THE ROTATION OF PRE-MAIN SEQUENCE STARS

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Kraft (1970) obtained the rotational velocities for large numbers of stars located in the field and in clusters of different ages. He noted that (a) among the field stars those stars with strong CaII K emission had larger rotational velocities than those without; (b) stars in the Hyades and Pleiades (which are much younger than the field) had both larger rotational velocities and stronger CaII K emission than field stars; (c) there was a pronounced break at spectral type early F in v sini as a function of spectral type and (d) the distribution of angular momentum per unit mass J(M) was proportional to $M^{0.57}$ for main sequence stars with mass $M > 1.5\ M_\odot$. This distribution predicted a v sini of ~75 km/sec for stars of lower mass (e.g. G type) but such high velocities were not seen in the Pleiades nor in the sun. This implied a more rapid deceleration of v sini for lower mass stars and led to estimates of the e-folding time of $\sim 4 \times 10^8$ years for stars of 1.2 $M_\odot$ to reduce their v sini from that of the Pleiades to that of the Hyades and $\sim 4 \times 10^9$ years to go from the Hyades to the sun's v sini. We note also that the age of the Pleiades is approximately equal to the pre-main sequence lifetime of a 1.0 $M_\odot$ star so that the zero-age main sequence cannot have $J(M) \propto M^{0.57}$ for ~1 $M_\odot$ stars. Skumanich (1972) showed that both the CaII K emission and the rotational velocity decayed as the $(\mathrm{age})^{-1/2}$ for main-sequence stars.

What happens before the main sequence? The only measurements until recently are those of Herbig (1957) for four T Tauri stars which have v sini in the range 25 to 60 km/sec. We decided to improve this situation by determining v sini for some 50 pre-main sequence stars in NGC 2264. Spectra (at 13A/mm) were obtained with the Carnegi image tube at the RC focus of the KPNO 4-meter reflector. The region between 5000 and 5200A was digitized and the rotational velocities determined by a Fourier Transform technique (Carroll 1933). Earlier results reported by Kuhi (1978) based on visual estimates were shown to be in error because of the effect of chromospheric emission filling in individual absorption lines to different degree. Stars were located on the HR diagram using Cohen and Kuhi's (1979) optical and infrared measurements. The resulting diagram shows considerable spread in age

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on a timescale of 10^6 years indicating non-coevality of star formation.

The measured rotational velocities also show a large range with the pre-main sequence stars falling into two groups divided roughly by the evolutionary track for a 1.5 $M_\odot$ star. Those stars with $M \geq 1.4\ M_\odot$ have $0 \leq v \sin i \leq 150$ km/sec and will evolve to the main sequence with a further ~25% decrease in radius resulting in v sini's which are consistent with the observed v sini for A stars and no further loss of angular momentum. Those stars with $M < 1.5\ M_\odot$ have $v \sin i \leq 20$ km/sec (our limit of detection) and will evolve to the main sequence with ~50% reduction in radius and a resultant increase in v sini to ≤ 30 km/sec assuming no loss of angular momentum. This is consistent with the observed rotational velocities in the Pleiades. This dichotomy is also shown by the Hα and non-Hα stars, the former having mostly upper limits for v sini. Thus, the pre-main sequence stars in NGC 2264 (with a well-developed photospheric spectrum) have lower v sini's than the zero age main sequence stars of the same mass.

We conclude: (1) that during the time taken by ~1.5 $M_\odot$ stars to reach the main sequence (~2×10^7 years) the loss of angular momentum in any significant amount cannot occur and hence that angular momentum must be conserved. Also e-folding times of ~10^8 years are implied so that pre-main sequence stellar winds need be only as large as those implied for the Pleiades, i.e. ~10 times larger than the solar wind. (2) The "break" in J(M) at ~1.5 $M_\odot$ on the main sequence is already present at the beginning of the radiative tracks and therefore it cannot be assumed that the zero-age main sequence distribution of angular momentum follows $M^{0.57}$ for $M \lesssim 1.5\ M_\odot$. (3) This implies that the bulk of the angular momentum must have been lost before the phase of a well-developed photosphere is reached, i.e. on the upper parts of the Hayashi track (or its dynamical equivalent) and hence that the angular momentum loss is more rapid than for high mass stars. (4) The timescale for this rapid loss phase is $\lesssim 10^6$ years if we determine the ages of the stars from their location on the HR diagram with respect to the convective-radiative evolutionary tracks (Iben and Talbot 1966).

Unfortunately, the most interesting candidates (the strong emission-line stars) for the strong angular momentum loss phase have no photospheric spectrum and hence cannot be measured for v sini. These stars often have high luminosities and may be spinning rapidly and losing angular momentum. However, the more normal T Tauri stars (for which the spectra look like normal photospheric spectra with the addition of a few emission lines) of low mass seem to have already lost all their "extra" angular momentum and consequently there is no need to have strong stellar winds for these objects during the radiative phase of their evolution to the main sequence.

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